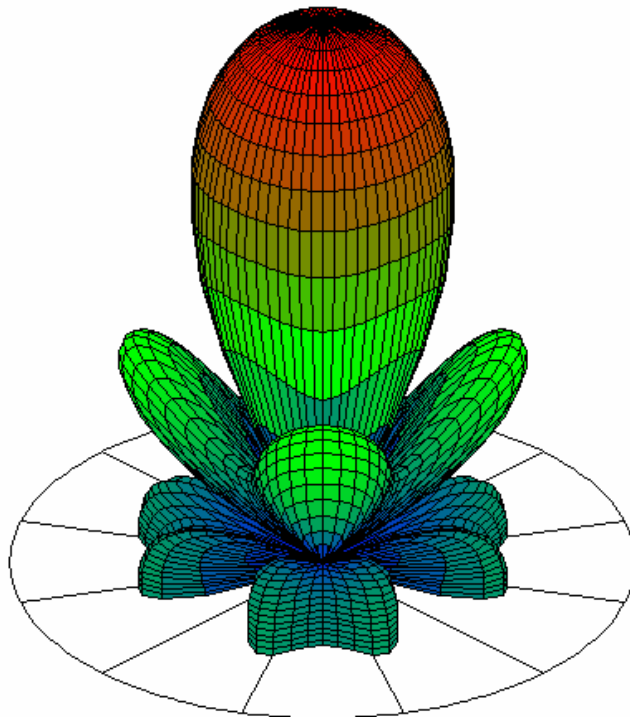


PCAAD 6.0

Personal
Computer
Aided
Antenna
Design



Version 6.0

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On the cover: 3D pattern plot for a circular array of radius 1.4λ , isotropic elements, spacing of 0.4λ .

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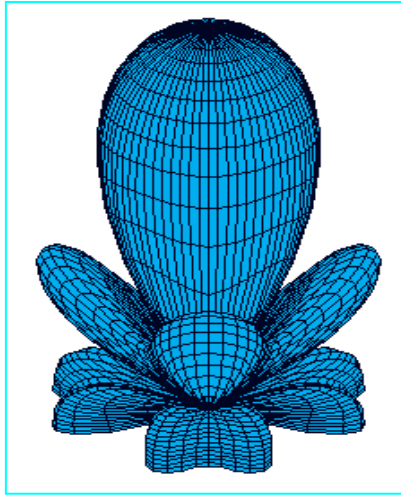
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I. Introduction to PCAAD 6.0



PCAAD 6.0 is a Windows-compatible software package that contains over 45 separate routines for the analysis and design of wire antennas, array antennas, aperture antennas, microstrip antennas, and transmission lines and waveguides. These routines are integrated into a menu-driven, user-friendly software package that allows you to quickly evaluate impedance and pattern characteristics for a large variety of antenna geometries. Some of the main features of PCAAD 6.0 include the following:

- A user-friendly Windows interface
- Full 32-bit compiled software
- Very simple and intuitive operation
- Fast results for first-cut designs
- Graphic illustrations of each antenna geometry
- Polar, rectangular, and 3-D pattern plots
- Smith chart, VSWR, and return loss plots for input impedance
- Data file output for patterns and impedance matrices
- On-line help
- Validation examples for each analysis routine

A. What's New in PCAAD 6.0

PCAAD 6.0 for Windows contains substantial improvements and enhancements compared to the previous version, PCAAD 5.0 [1]. Some of the specific improvements in this version of PCAAD are listed below:

- analysis of diagonal horn antennas
- phase center calculation for horn antennas
- analysis of rectangular and circular aperture antennas
- data for antenna noise temperature
- calculation of radio link loss
- calculation of polarization mismatch
- data for atmospheric and rain attenuation
- calculation of axial ratio due to amplitude and phase errors

- calculation of array sidelobe level due to random errors
- co- and cross-pol patterns for all antennas
- pattern phase data can be saved to pattern file
- calculator for useful microwave and antenna functions
- plot up to five data sets on Smith chart plots
- log files written for all wire antenna solutions
- improved accuracy for conical horns
- arbitrary grid angle allowed in Grating Lobe routine
- can copy active window to clipboard
- improved graphics, error checking, and Help
- Glossary of antenna terms included with Short Course

PCAAD 6.0 is intended for use by systems and design engineers, researchers, and students who need a quick solution to a canonical antenna design or analysis problem. Most of the routines in PCAAD 6.0 involve basic antenna elements whose theory and characteristics are thoroughly described in a number of texts on antennas [2]-[9]. All of the solutions used in PCAAD 6.0 are based on these results, or on similar well-established and proven methods.

B. Disclaimer

This software package has been written and tested with care. Nevertheless, this software and its associated user's manual are provided as is, without warranty of any kind. Neither the author nor Antenna Design Associates, Inc., make any warranties, expressed or implied, that the software or the manual are free of error, or will meet the requirements of any particular application. The software should not be relied upon for the generation of data where such data, if incorrect or inapplicable, could result in loss of property or personal injury. Any use of the software or the manual in such a manner is at the user's own risk. The author and Antenna Design Associates, Inc., disclaim all liability for direct, incidental, or consequential damages resulting from any use of the software or manual.

II. Getting Started With PCAAD 6.0

A. System Requirements

PCAAD 6.0 will operate on PC-compatible computers running Windows 98, Windows 2000, Windows XP, or Windows Vista. PCAAD 6.0 requires a 32-bit operating system, and will not run under Windows 3.1. Best results will be obtained with a color monitor having a resolution of at least 800 x 600. Installation requires a CD-ROM drive. PCAAD 6.0 occupies less than 8 MB of disk space.

Since PCAAD 6.0 runs under Microsoft Windows operating systems, we assume you are familiar with basic Windows usage. Thus, you should know how to run programs from Windows, how to create and rearrange program shortcuts, how to create, copy, and delete files, and how to use Windows menus, text boxes, and control buttons. It is also helpful to be aware of how to open, close, move, and resize windows.

B. Installing PCAAD 6.0

Installing PCAAD 6.0 on your system is easy. Insert the distribution CD into your CD drive, and execute the SETUP.EXE program that is located on the CD. Installation may require **Administrator** access, depending on your operating system. By default, the setup program will install PCAAD 6.0 into a subdirectory called **PCAAD6** in the Windows **Program Files** directory, but a different directory may be specified, if desired. The setup program will decompress and install all necessary files, and a PCAAD 6.0 entry will be created on your **Start Menu**, and a PCAAD 6.0 icon will be installed on your desktop. PCAAD uses a number of small bitmap files, which are stored in the **PCAAD6\BMP** subdirectory. PCAAD 6.0 can be started from the **Start Menu**, or from the **PCAAD 6.0** icon on your desktop.

The PCAAD 6.0 installation procedure also creates a subdirectory, **PCAAD6\SHORTCOURSE**, which contains PDF files for an introductory short course on antennas. The course is arranged by Chapters 0 through 7, where Chapter 0 lists the contents and syllabus for the course. Chapters 1 through 7 provide a basic introduction to antenna theory and design, and include examples, review questions, and problems. The course concludes with the Antenna IQ test. Answers to the test and all problems are given in the Answers.pdf file. There is also a short Glossary on commonly used terms related to antenna technology. These files may be accessed from the PCAAD 6.0 Help menu, or directly from the **PCAAD6\SHORTCOURSE** directory. The Acrobat PDF reader is required to view the short course files.

To uninstall PCAAD 6.0, use the **Add/Remove Programs** facility located in the Windows **Control Panel**. This will properly remove the PCAAD 6.0 systems files from your computer and the registry. Any data files that you created when using PCAAD 6.0 will have to be deleted separately.

C. The PCAAD6.INI file

PCAAD 6.0 uses a file called PCAAD6.INI, located in the PCAAD 6.0 program directory, to set some options and directory locations that are required for proper operation of PCAAD. Generally you will not have to modify this file, and, like most .INI files, improper entries can cause errors when running PCAAD. Here we describe the entries in the PCAAD6.INI file, with their default values:

[PCAAD6]	
FileDir=C:\Windows\Program	path to user file directory
SystemEditor=C:\WINDOWS\NOTEPAD.EXE	path to system text editor
Bitmaps=1	PCAAD bitmap option (0-off; 1-on)
SavePhaseData=0	phase data save option (0-don't save; 1-save phase data)
PatternPlotType=1	default pattern plot type (1-polar; 2-rectangular, 3 -3D)
ImpedancePlotType=0	default impedance plot type (0-Smith chart; 1-VSWR/RL)
PatternAzimuthAngle=0.0	azimuth angle for pattern plots
PatternStepSize=1.0	step size for pattern plots
3DAzimuthStep=6.0	azimuth step size for 3-D plots
3DElevationStep=2.0	elevation step size for 3-D plots
UpperHemisphereOnly=0	3D plot type (0-both hemispheres; 1-upper only)
PlanarPlotData#1Color=255	color for data set #1 (pattern plots)
PlanarPlotData#2Color=16711680	color for data set #2 (pattern plots)
AngleCursor=65535	color for angle cursor
PlotBackgroundColor=12632256	color for plot background
RL/VSWRPlotData#1Color=255	color for data set #1 (RL/VSWR)
RL/VSWRPlotData#2Color=16711680	color for data set #1 (RL/VSWR)
RectangularPatternPlotLabel=Pattern	(dB) vertical label on rectangular
PatternPlaneType=1	type of pattern cut
SmithPlotData#1Color=255	color for data set #1 (Smith plot)
SmithPlotData#2Color=16711680	color for data set #2 (Smith plot)
SmithPlotData#3Color=32768	color for data set #3 (Smith plot)
SmithPlotData#4Color=16744700	color for data set #4 (Smith plot)
SmithPlotData#5Color=4194304	color for data set #5 (Smith plot)

The above values are typical entries that are set upon installation, but most of these

values will change according to the plotting and color options that are set and saved when using the **Plot Default Types** and **Plot Default Colors** options from the **Plot** menu. It is recommended that the user not directly modify the PCAAD6.INI file, except perhaps to set the vertical axis label for the rectangular pattern plot routine.

III. Using PCAAD 6.0 – General Instructions

A. Organization of PCAAD 6.0

The main window is displayed when PCAAD 6.0 starts, and forms the background for all modules and routines. The menu bar at the top of the window categorizes the antenna modules into several groups, along with useful plotting routines and other utilities. Specific routines are listed and summarized below:

Plot

Polar Pattern Plot	-plot patterns in polar form
Rectangular Pattern Plot	-plot patterns in rectangular form
3-D Pattern Plot	-plot patterns in 3-D form
Smith Chart Plot	-plot and tune impedance on a Smith chart
VSWR/Return Loss Plot	-plot VSWR or Return Loss
Plot Default Types	-set defaults for pattern and impedance plot types
Plot Default Colors	-set color preferences for plots
Exit	-exit PCAAD 6.0

Edit

Copy Window	-copy current Window to Windows clipboard
Copy Graph	-copy current plot to Windows clipboard
Copy Text	-copy selected text to Windows clipboard
Paste Text	-paste text from Windows clipboard
Edit File	-invoke system text editor (Notepad)
Print Window	-print current PCAAD window and its contents

Wire

Wire Dipole Antenna Analysis	-analyze wire dipole antenna
Wire Dipole RCS Analysis	-compute RCS of wire dipole
V-dipole Antenna Analysis	-analysis of V-dipole wire antenna
Wire Loop Antenna Analysis	-analysis of wire loop antenna
Yagi Dipole Array Analysis	-analyze wire dipole Yagi array
Finite Wire Dipole Array	-analyze finite planar dipole array
Log Periodic Dipole Array Design	-design log periodic dipole array
Log Periodic Dipole Array Analysis	-analysis of log periodic dipole array
General Wire Antenna Analysis	-analyze arbitrary wire antenna geometry

Arrays

Uniform Linear Array	-patterns and directivity of a uniform linear array
Linear Subarray	-patterns of a linear array of subarrays
Uniform Rectangular Array	-patterns and directivity of a rectangular array
Uniform Circular Planar Array	-patterns and directivity of a circular planar array
Arbitrary Planar Array	-patterns and directivity of an arbitrary planar array
Infinite Printed Dipole Array	-active impedance of infinite printed dipole array
Linear Array Pattern Synthesis	-Woodward-Lawson array synthesis
Grating Lobe Diagram	-grating lobe diagram for a planar array
Effect of Array Excitation Errors	-effect of array excitation errors, failed elements

Apertures

Traveling wave Line Source	-patterns of an arbitrary line source
Rectangular Aperture Antenna Analysis	-analysis of a rectangular aperture antenna
Circular Aperture Antenna Analysis	-analysis of a circular aperture antenna
E-plane Sectoral Horn	-analysis of an E-plane sectoral horn
H-plane Sectoral Horn	-analysis of an H-plane sectoral horn
Pyramidal Horn	-analysis of a pyramidal horn
Corrugated Pyramidal Horn	-analysis of a corrugated pyramidal horn
Conical Horn	-analysis of a conical horn
Corrugated Conical Horn	-analysis of a corrugated conical horn
Parabolic Reflector (approximate)	-approximate analysis of prime-focus reflector
Parabolic Reflector (patterns)	-patterns of prime-focus reflector

Microstrip

Rectangular Probe-fed Patch	-probe-fed patch analysis (Carver's model)
Rectangular Probe-fed Patch	-probe-fed patch analysis (cavity model)
Rectangular Line-fed Patch	-line-fed patch analysis (t-line model)
Rectangular Proximity-fed Patch	-proximity-fed patch analysis (t-line model)
Rectangular Aperture Coupled Patch	-aperture coupled patch analysis (cavity model)
Circular Probe-fed Patch	-probe-fed patch analysis (cavity model)

Transmission Lines

Microstrip Line	-analysis and design of microstrip line
Covered Microstrip Line	-full-wave analysis of covered microstrip line
Stripline	-analysis and design of stripline
Coaxial Line	-analysis of coaxial line
Rectangular Waveguide	-analysis of rectangular waveguide
Rectangular Waveguide Data	-standard rectangular waveguide data
Circular Waveguide	-analysis of circular waveguide
Surface Waves	-analysis of surface waves

Miscellaneous

Communication Link Loss	-Friis formula for radio links
Polarization Mismatch	-polarization mismatch between two antennas
Atmospheric and Rain Attenuation	-propagation loss due to atmosphere or rain
Axial Ratio vs. Excitation Errors	-axial ratio vs. amplitude and phase errors
Antenna Noise Temperature	-antenna sky noise temperature
Calculator	-useful antenna and microwave functions

Help

Help Contents	-contents of Help
Help Index	-index for Help
Context Help	-context help for PCAAD 6.0 (F1 key)
Short Course	-short course on antennas
About PCAAD	-information about PCAAD 6.0 and your system

After selecting a particular antenna or transmission line topic from the main PCAAD menu, a window will open for that routine. The windows for all routines have the same format: a small graphic image of the antenna or transmission line geometry is shown at the top left of the window, with data

entry at the top right, and output data listed below. Most routines have a **Compute** button that is used to initiate computations after all data has been entered. Results are displayed after the computation is finished, and most routines then allow the option of plotting data, saving data in a file, or running a new solution. Input data values are retained until the window is closed, making it easy to change one parameter and run a new solution. Most routines have error checking of input data, but the software is not completely foolproof.

B. Entering Data and Running the Routines

Numerical values are entered in PCAAD 6.0 using text boxes. When a routine starts, a flashing cursor bar will appear in the text box for the first data entry item. Type in the numerical value, and press **Enter** on the keyboard to move to the next entry. You can also use the **Tab** key, or the mouse, to move to the next data entry. Error checking is performed for most data entries, generally after the **Compute** button is pressed. If a value is found to be in error, a small error message box is displayed. Click the **OK** button on this box, and focus will return to the data item that was found to be in error. After you have computed a solution, you can change one or more problem parameters by simply entering new values for those items, without having to re-enter all other parameters.

C. Pattern Calculation and Plotting

Many routines involve the calculation of far-field radiation patterns. These may be plotted as planar pattern cuts on a polar plot or a rectangular plot, or as a 3-D volumetric plot. The type of plot desired for a particular routine is specified by clicking the **Pattern Type Select** button. Elevation plane patterns can be plotted at a specified azimuthal angle for E-theta / E-phi or Co-pol / X-pol patterns (using Ludwig's third definition), or E-plane / H-plane patterns can be selected. Plotting parameters, such as azimuth angle and step sizes, are also specified with this window. Default values can be set with the **Plot Default Types** option from the **Plot** menu. Pattern plots can be invoked directly from a PCAAD antenna analysis routine, or patterns can be plotted from data files through the **Plot** menu. Up to two separate patterns can be plotted on the polar or rectangular plots, but only one pattern can be plotted as a 3-D plot. Plots may be printed (click the **Print Plot** button in the plotting window), or copied to the Windows clipboard for use in other applications (use **Copy Graph** from **Plot** on the main menu bar).

D. Saving Pattern Data

Routines that provide far-field radiation patterns also allow the option of saving pattern data (planar or 3D) to a file with the **Save Patterns** button. PCAAD 6.0 now allows saving of far-field phase data, in addition to the pattern amplitude (for planar patterns). Phase data can be useful when using PCAAD results with other programs, such as characterizing a feed for reflector antenna analysis. Planar pattern data is saved as an ASCII text file, with one row for each angle. The format is: pattern angle in degrees, pattern amplitude in dB, and pattern

phase in degrees. These values are delimited with one or more spaces. The PCAAD polar and rectangular pattern plotting routines can read these files, with or without the phase column. You can control whether the phase information is saved or not by using the check box on the **Default Plot Types** menu. For 3D volumetric patterns, the following data file format is used: the first line has three values: the elevation angle step size (degrees), the azimuth angle step size (degrees), and the maximum elevation angle range (90 degrees for upper hemisphere only, or 180 degrees for both hemispheres). This is followed by $N = 1 + 360 / (\text{azimuth angle step size})$ lines, one for each azimuth angle. Each of these lines contains $1 + 90/(\text{elevation angle step size})$ pattern values in dB (for each elevation angle). (Note: this format is slightly different from that used in PCAAD 5.0, which only allowed plotting of the upper hemisphere, and thus did not require the third entry of the first line. To make PCAAD 5.0 3D data files compatible with PCAAD 6.0, simply edit the .3DP data file and add the value “90” to the end of the first line.)

E. Impedance Calculation and Plotting

Several routines, such as the wire antenna and microstrip antenna routines, perform calculations of input impedance over a swept frequency range. The parameters of this sweep are specified as the center frequency, the frequency step size, and the number of frequency points. You can enter specific values for these parameters in the appropriate boxes, or allow PCAAD to provide estimates by clicking the **Compute** button. Note that the center frequency parameter refers to the middle of the frequency sweep range, which may be different from the operating frequency of the antenna. Impedance versus frequency can be plotted on a Smith Chart plot or on a VSWR/Return Loss plot; the default type of impedance plot can be set from the **Plot Default Types** option from the **Plot** menu. The Smith chart window also contains a powerful impedance matching utility.

F. Help

PCAAD 6.0 contains a comprehensive help file in standard Windows format with convenient cross-references and search options. The help file is context-sensitive, meaning that you can simply press the **F1** key while using any analysis routine to get help on that particular routine. Pressing the **F1** key while on the main window will bring up the help contents for PCAAD 6.0. Help can also be accessed by clicking **Help - Context Help** from the main menu bar.

You can also access the mini-short course on antenna theory from the **Help** menu. The short course is grouped by chapters into individual PDF files, along with a Glossary, and a quiz on antennas. Select **Short Course** from the **Help** menu, and the desired file from the directory listing. The file should open with the Acrobat Reader. You need to have the Acrobat Reader installed on your computer.

IV. Using PCAAD 6.0 – Instructions and Examples

This chapter will describe in detail the operation of each antenna, transmission line, and utility routine in PCAAD 6.0 in terms of the input and output data, and a brief discussion of the theory of the solution. Validation examples are also included for the analysis routines.

A. The Plot Menu

The first five of the options on the **Plot** menu allow you to plot data from files using PCAAD's plotting routines. Antenna patterns can be plotted in polar or rectangular form, or in 3-D volumetric form. Impedance data can be plotted on a Smith chart, or on a VSWR / Return Loss plot. The **Default Plot Types** option is used to control the default plot type when patterns or impedances are plotted directly from PCAAD's antenna routines. **Default Plot Colors** is used to set the preferred colors used in the pattern and impedance plots. **Exit** is used to exit the program.

A.1. Polar Pattern Plot

This routine plots up to two planar antenna radiation patterns in polar form. It can be called directly from most of the PCAAD antenna routines to plot patterns, or used independently from the **Plot** menu to plot patterns from a data file. The routine also computes the main beam pointing angle, the 3 dB beamwidth of the main beam, and provides a movable angle cursor to read pattern values at any angle. The **Plot Options** window allows control of various plot parameters such as the number of divisions, scales, plotting ranges, offsets, and colors. The resulting plot can be printed on your printer, or exported to another application using the Windows clipboard and the **Copy Graph** command from the **Edit** menu.

To read pattern data from a data file, click the **Read Data File** button, and use the file dialog box to specify a filename. The data file should be in ASCII form, with each line consisting of an angle (in degrees), the pattern (in dB), and the phase (in degrees) at that angle. The data must be in sequence, in order of increasing angle. These values are delimited with one or more spaces. The PCAAD polar and rectangular pattern plotting routines can read these files, with or without the phase column. You can control whether the phase information is saved or not by using the check box on the **Default Plot Types** menu. The pattern files written by PCAAD 6.0 are in this format, and can be read by either the polar or the rectangular pattern plotting routines.

Up to two separate patterns can be plotted simultaneously, either from data files or PCAAD antenna routines. Each data set may be offset by a fixed amount (through the **Plot Options** menu), allowing patterns to be plotted in terms of absolute gain, or to facilitate comparison of patterns normalized to different

values. The default file extension for planar pattern data files is .DAT.

Display boxes for each pattern are shown at the top left of the polar plotting window. These indicate the name of the pattern (either the filename, or a description provided by the calling routine), the main beam pointing angle, the 3 dB beamwidth for the pattern, and the offset of the data (as set in the **Plot Options** window). If the pattern does not have a well-defined main beam, or has more than one main beam (e.g., grating lobes), the beam position and beamwidth may not be meaningful, and may not be shown. The display boxes also show the value of the pattern at the angle indicated by a movable angle cursor. The angle cursor is drawn as a dashed radial line, and can be moved by either clicking or dragging with the mouse, or by using the left and right arrow keys (NumLock must be off). When using the mouse, notice that the mouse cursor changes from an arrow to a cross-hair when moved inside the polar plotting region. Clicking the mouse inside the polar plot will snap the angle cursor to that angular position. Alternatively, the angle cursor can be moved by clicking the mouse on the angle cursor (note that the mouse cursor changes to a directional icon when over the angle cursor), and dragging to the desired position. The pattern value display is updated instantly. This feature is useful for reading sidelobe or cross-pol levels.

Plot options for the polar and rectangular plotting routines can be selected by clicking the **Plot Options** button in the plot routine window. The angle cursor display function can be turned on or off using the **Show Cursor** check box. Scroll boxes can be used to adjust the number of amplitude divisions from 2 to 8, the step size per division from 3 dB to 20 dB, and the maximum value of the plot from -40 dB to 40 dB. It is also possible to add a fixed offset value, ranging from -40 to 40 dB, to each pattern. The colors of the plotted pattern curves, the background of the plot, and the angle cursor are shown, and can be changed from their default colors of red, blue, gray and yellow by clicking the appropriate **Change** button. This may make the display more legible for monochrome or notebook computer displays, and for importing the graph into word processors and other Windows software. The pattern plot colors match those used in the display boxes at the left of the plotting routine window.

Each pattern can be identified with a movable text label. The text is set from **Plot Options**, and the labels can be turned on or off using the check box for **Show Pattern Labels**. Use the mouse to drag the label to the desired position on the plot.

A.2. Rectangular Pattern Plot

This routine plots up to two planar antenna radiation patterns in rectangular form. It can be called directly from most of the PCAAD antenna routines to plot patterns, or used independently from the **Plot** menu to plot patterns from a data file. The routine also computes the main beam pointing angle, the 3 dB beamwidth of the main beam, and provides a movable angle cursor to read pattern values at any angle. The **Plot Options** window allows control of various plot parameters such as the number of divisions, scales, plotting ranges, offsets, and colors. The resulting plot can be printed on your printer, or exported to another application using the Windows clipboard and the **Copy Graph** command from the **Edit** menu.

To read pattern data from a data file, click the **Read Data File** button, and use the file dialog box to specify a filename. The data file should be in ASCII form, with each line consisting of an angle (in degrees), the pattern (in dB), and the phase (in degrees) at that angle. The data must be in sequence, in order of increasing angle. These values are delimited with one or more spaces. The PCAAD polar and rectangular pattern plotting routines can read these files, with or without the phase column. You can control whether the phase information is saved or not by using the check box on the **Default Plot Types** menu. The pattern files written by PCAAD 6.0 are in this format, and can be read by either the polar or the rectangular pattern plotting routines.

Up to two separate patterns can be plotted simultaneously, either from data files or PCAAD antenna routines. Each data set may be offset by a fixed amount (through the **Plot Options** menu), allowing patterns to be plotted in terms of absolute gain, or to facilitate comparison of patterns normalized to different values. The default file extension for planar pattern data files is .DAT.

Display boxes for each pattern are shown at the top left of the rectangular plotting window. These indicate the name of the pattern (either the filename, or a description provided by the calling routine), the main beam pointing angle, the 3 dB beamwidth for the pattern, and the offset of the data (as set in the **Plot Options** window). If the pattern does not have a well-defined main beam, or has more than one main beam (e.g., grating lobes), the beam position and beamwidth may not be meaningful, and may not be shown. The display boxes also show the value of the pattern at the angle indicated by a movable angle cursor. The angle cursor is drawn as a dashed vertical line, and can be moved by either clicking or dragging with the mouse, or by using the left and right arrow keys (**NumLock** must be off). When using the mouse, notice that the mouse cursor changes from an arrow to a cross-hair when moved inside the rectangular plotting region. Clicking the mouse inside the rectangular plot will snap the angle cursor to that angular position. Alternatively, the angle cursor can be moved by clicking the mouse on the angle cursor (note that the mouse cursor

changes to a directional icon when over the angle cursor), and dragging to the desired position. The pattern value display is updated instantly.

Each pattern can be identified with a movable text label. The text is set from **Plot Options**, and the labels can be turned on or off using the check box for **Show Pattern Labels**. Use the mouse to drag the label to the desired position on the plot. The vertical axis is normally labeled as *Pattern (dB)*, but this label can be changed by modifying the PCAAD5.INI file - this can be useful when plotting directivity or gain.

A.3. 3-D Pattern Plot

This routine plots an antenna radiation pattern in a 3-D volumetric form. It can be invoked directly from most of the PCAAD antenna routines to plot patterns, or used independently from the **PLOT** menu to plot patterns from a data file. Data files of this type can be generated from most of the PCAAD routines, and are given the default file extension .3DP, to distinguish them from planar pattern data files. The 3-D pattern plot can also be printed on your printer, or exported to another application using the Windows clipboard and the **Copy Graph** command from the **Edit** menu.

For 3D volumetric patterns, the following data file format is used. The first line has three values: the elevation angle step size (degrees), the azimuth angle step size (degrees), and the maximum elevation angle range (90 degrees for upper hemisphere only, or 180 degrees for both hemispheres). This is followed by $N = 1 + 360 / (\text{azimuth angle step size})$ lines, one for each azimuth angle. Each of these lines contains $1 + 90/(\text{elevation angle step size})$ pattern values in dB (for each elevation angle). (Note: this format is slightly different from that used in PCAAD 5.0, which only allowed plotting of the upper hemisphere, and thus did not require the third entry of the first line. To make PCAAD 5.0 3D data files compatible with PCAAD 6.0, simply edit the .3DP data file and add the value "90" to the end of the first line.)

The routine has three slider controls to allow adjustment of the plot size, the elevation view angle, and the azimuth view angle. The plot is redrawn after each adjustment of these controls. Drawing of the plot can be time consuming on slow computers, especially if the elevation and azimuth step sizes are small. A color bar near the bottom of the window shows the scale, with red corresponding to 0 dB, and blue to -30 dB.

A.4. Smith Chart Plot

The Smith Chart plotting routine is a very versatile tool, capable of plotting up to five sets of impedance data, and incorporating an easy-to-use impedance matching capability. It can be called directly from routines that calculate impedance, such as the wire antenna and microstrip element routines, or it can

be used independently from the **Plot** menu to plot impedance data from ASCII data files.

When used with data files, the file should be in ASCII form with one line for each data point. The real part, the imaginary part, and an optional data point label (up to five characters long) should be delimited with commas or spaces. The data point labels are commonly used as frequency markers, but other parameters can be used as well (such as scan angle). The impedance data is assumed to be in absolute (ohms, not normalized) form. Click the **Read Data File** button to select a data file. Up to five data sets can be displayed, except when the impedance matching solution is used. The impedance matching response must always be the last data set, so further data is prevented from being read when the impedance matching response is on.

From the Smith chart window, you can use the mouse to click on any data point, and read the exact value of its impedance in the data box at the top left of the window. This display also gives the corresponding normalized impedance, and the reflection coefficient for that impedance. The chart also shows a constant VSWR circle (dashed circle), which may be adjusted by either dragging with the mouse cursor, or by entering a new value in the VSWR data entry box at the left side of the chart. Similarly, the chart also shows a dashed radial line indicating wavelengths toward the load (WTL), and wavelengths toward the generator (WTG). This line may be set by dragging with the mouse, or by entering a value of WTL or WTG in the appropriate data box. In addition, the VSWR and WTL/WTG cursors may be set to a particular data point by double clicking on that point. Smith chart options such as interpolation, characteristic impedance, a rotated $1+jx$ circle, colors, and other display options can be set by clicking the **Plot Options** button. Colors can also be set from the **Default Plot Colors** window available under **Plot** on the main menu bar - this window also allows saving of your color selections as defaults. Each impedance data set can be identified with a movable text label. The label is initially set as the filename for that data set (if the data was read from a file), or the name of the calling routine (if the data was obtained from another PCAAD routine). You can also set the labels from the **Plot Options** window, and the labels can be turned on or off using the check box for **Show Data Point and Set Labels** (enter blanks for the data set label if you want data point labels but not a data set label). Use the mouse to drag the label to the desired position on the Smith chart.

PCAAD also features a general purpose impedance matching routine coupled to the Smith chart. With one or more (but less than five) data sets displayed, first select a data set and a matching frequency by clicking on the desired data point (if you do not select a data point, the program will use the midpoint of the first data set). Then turn on the impedance matching feature by clicking the **On** button in the **Impedance Matching** frame. The response of the matched

impedance data will be displayed. You may change the matching frequency using the scroll box (the impedance data set must have frequency labels for each data point). You may choose the type of matching circuit from the list box – a quarter-wave transformer, LC networks, open- and short-circuit shunt stubs, and open- and short-circuit series stubs are available (see [10] for a discussion of impedance matching techniques). Except for the quarter-wave transformer, each of these circuits yields two different matching solutions, which can be selected with the buttons marked **Solution #1** and **Solution #2**. Each matching solution has two parameters (transformer impedance and length, series and shunt components values, or stub length and position). These values are listed for the selected matching network and solution. (For the stub tuners, the characteristic impedance of the transmission line and stub are assumed to be the same as the characteristic impedance of the Smith chart.) Only a single impedance data set can be matched at one time; to change the data set to be matched, turn off the impedance matching feature, select a data point on the new data set, and turn impedance matching back on. Once the matching parameters have been selected, the routine calculates the input impedance seen looking into the matching network at each frequency, and plots this as a new impedance locus on the chart. The user can study the effect of changing matching circuits, the match frequency, and different matching solutions very easily with this routine. The effect of changes in component values can be studied simply by entering new values in the component value boxes. Note that, for data sets having a wide frequency range between data points, it is possible that the plotted impedance loci for the original or matched data sets may run off the edge of the chart – this is because the accuracy of interpolation may not be sufficient. If this is a problem, interpolation may be turned off in the **Plot Options** window. When the impedance matching feature is in use, no further data sets may be read.

A.5. VSWR / Return Loss Plot

This routine plots up to two sets of impedance data as either VSWR or return loss (in dB) versus frequency. It can be called directly from PCAAD routines that calculate impedance, such as the wire antenna and microstrip element routines, or it can be used independently from the **Plot** menu to plot impedance data from a file. The resulting plot can be printed on your printer, or exported to another application using the Windows clipboard and the **Copy Graph** command from the **Edit** menu.

Select either a **VSWR** or **Return Loss** plot by clicking the appropriate option button to the left of the plot. Plot options, such as interpolation and color of plotted data, characteristic impedance, and the range and number of divisions for the vertical and frequency scales, can be set by clicking the **Plot Options** button.

When used with a data file, the file should be in ASCII form with one line for

each data point. The real part, the imaginary part, and the frequency (up to five characters) should be delimited with commas or spaces. The impedance data is assumed to be in absolute (ohms, not normalized) form. This is the same format used by the Smith chart routine, and the format that PCAAD uses when saving impedance data to a file.

A.6. Default Plot Types

The default type of pattern plots (polar, rectangular or 3-D), and impedance plots (Smith chart or VSWR/Return Loss) are selected with this window. You can select planar pattern cuts in polar or rectangular form, or a three dimensional volumetric pattern plot. Your selections on this window can be saved as default values by clicking the **Save Defaults** button.

For planar patterns, you have the choice of viewing either E-theta / E-phi, Co-pol / X-pol (Ludwig's third definition) or E-plane / H-plane patterns, at a particular azimuth angle. (E-plane / H-plane patterns are not available in some PCAAD routines.) The elevation angle step size can also be specified. You can also control whether or not phase data is saved with the planar pattern data to a file by using the check box.

For 3-D volumetric patterns, the elevation and azimuth step sizes can be specified - these values should generally be between 2 to 10 degrees for best results. Volumetric patterns are computed using the magnitude of the total electric field, and may be plotted over either the upper hemisphere, or both hemispheres, depending on the type of antenna. You can choose to display only the upper hemisphere of a 3D pattern plot by using the check box. Note that many antennas in PCAAD (microstrip antennas, horn antennas, and antennas over a ground plane) have volumetric patterns that extend only over the upper hemisphere.

A.7. Default Plot Colors

This window is used to set the default colors used in the pattern (polar and rectangular) and impedance (Smith chart and VSWR/Return Loss) plotting routines. Line colors for data sets can be set, as well as the cursor color and background color. Color selections can be saved as defaults for later use.

A.8. Exit

Click this option to exit PCAAD. The program can also be closed by clicking the box at the top right of the main window.

B. The Edit Menu

Being a Windows application, PCAAD 6.0 allows use of the standard Windows methods of cutting, copying, and pasting data and graphics from PCAAD routines to the Windows clipboard. For example, you can copy an image of the active window to the Windows clipboard by pressing **Alt-PrintScreen**, or copy an image of the entire screen to the clipboard by pressing **PrintScreen**. You can also transfer data from one input box to another by using the Windows clipboard. This can be done using the PCAAD functions described below, or by using the **Ctrl-C** and **Ctrl-V** keys to respectively copy and paste selected data.

B.1. Copy Window

Copy Window allows you to copy the currently active Window to the Windows clipboard. This may then be pasted into another Windows application, such as PowerPoint or a word processor. This action is similar to pressing **Alt-PrintScreen**, which also copies the active Window to the clipboard. Note that the entire screen image can be copied to the clipboard by pressing **PrintScreen** (these are standard Windows commands).

B.2. Copy Graph

Copy Graph allows you to copy the current graph or plot to the Windows clipboard. The graph or plot may then be pasted into another Windows application, such as PowerPoint or a word processor. Note that this command only copies the graph or plot, not the complete Window.

B.3. Copy Text

To copy a value from a data box to the Windows clipboard, first select the data using the mouse. Then click **Copy Text** from the **Edit** menu. This function can also be accomplished by pressing **Ctrl-C** after selecting the desired data, or by right-clicking the mouse and selecting **Copy**.

B.4. Paste Text

To copy a value from the Windows clipboard to a data box in PCAAD, click on the desired data box, then click **Paste Text** from the **Edit** menu. This function can also be accomplished by pressing **Ctrl-V**, or by right-clicking the mouse and selecting **Paste**.

B.5. Edit file

Click the **Edit File** option from the **Edit** menu to invoke the Windows system text editor (typically **Notepad**). This allows you to easily view or edit data files when using PCAAD 6.0. The location of the system editor is specified in the PCAAD5.INI file, as described in Section II.C.

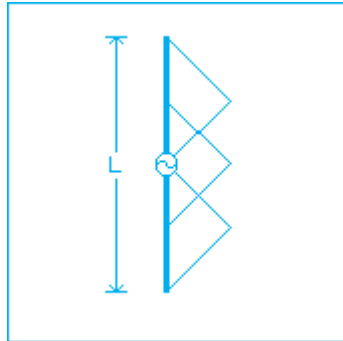
B.6. Print Window

This option is used to print the current active analysis or plotting routine window. This function is useful for obtaining a hard copy of the complete set of input output data associated with a PCAAD 6.0 routine. Input data, output data, and graphics are printed.

C. The Wire Antennas Menu

These nine routines involve the analysis and design of various wire antennas. Wire dipoles, loops, Yagi-Uda arrays, planar dipole arrays, log periodic dipole arrays, and more general wire antenna geometries are modeled using a standard thin-wire Galerkin moment method solution with piecewise sinusoidal modes [3], [11].

C.1. Wire Dipole Antenna Analysis



This routine computes the input impedance, broadside gain, and radiation pattern of a dipole antenna. The feed point can be placed at the center of any expansion mode. The solution uses the piecewise sinusoidal (PWS) Galerkin moment method, with the exact exponential integral expressions used for the impedance matrix elements, as detailed in references [11], [12]. This method has proven to be the most accurate and efficient technique for solving thin wire antenna and scattering problems.

Begin by entering the dipole length, the dipole radius, the number of PWS expansion modes, and the position of the feed generator. The generator feed point must be located at the center of a PWS expansion mode. If the dipole is center-fed, the number of expansion modes should be odd, and the mode number of the generator should be the middle mode (this mode number is automatically selected as the default mode number for the generator). Pattern plots can be made in the E- and H-planes of the dipole, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button. The resonant frequency of the dipole, the frequency step size, and the default number (7) of frequency points are displayed to the right of the **Compute** button. These values can be estimated by the routine by clicking the **Compute** button, or you can enter your own values for center frequency, frequency step size, and the number of frequency points. The geometry of the dipole may be viewed in three dimensions by clicking the **Show Geometry** button.

Upon clicking the **Compute** button, the routine will compute the moment method solution for the dipole, and list the input impedance versus frequency in the list box. The scroll bar can be used to scroll through the data. The gain of the dipole at its beam maximum is computed at the center frequency of the frequency sweep. At this point you can plot the impedance characteristics versus frequency on a Smith chart plot or a VSWR/Return Loss plot, and can save the impedance data in a data file. The specified patterns are also calculated at the center frequency, and may be

plotted using the **Plot Patterns** button, or saved to data files. After each computation, data is automatically written to a log file called WIRE.LOG, located in the PCAAD program directory. This data includes the frequency, wire radius, coordinates of all points on the wire structure, the definition of the PWS expansion modes, the moment method impedance matrix, and the voltage and current vectors.

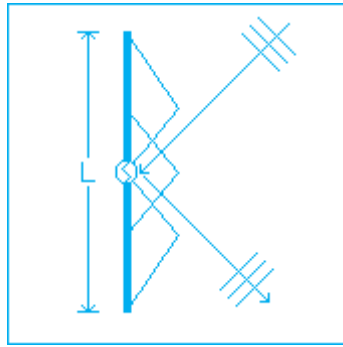
Validation

Consider a half-wave dipole with a radius of 0.001λ . Calculated input impedance results from PCAAD 6.0 are compared with those from [1] and [11], versus N, the number of expansion modes:

N	Reference [1]	PCAAD 6.0
1	$73.1 + j\ 42.2\ \Omega$	$73.1 + j\ 42.2\ \Omega$
3	$81.2 + j\ 41.3\ \Omega$	$81.2 + j\ 41.3\ \Omega$
5	$82.8 + j\ 42.0\ \Omega$	$82.8 + j\ 42.0\ \Omega$
7	$83.6 + j\ 42.7\ \Omega$	$83.6 + j\ 42.7\ \Omega$

The gain of a half-wave dipole is, from [2], 2.15 dB; PCAAD 6.0 gives 2.2 dB.

C.2. Wire Dipole Radar Cross-Section Analysis



This routine is very similar to the dipole antenna routine except that it computes the bistatic radar cross section (RCS) for a loaded wire dipole. The solution uses the piecewise sinusoidal expansion (PWS) Galerkin moment method, with the exact exponential integral expressions used for the impedance matrix elements, as detailed in references [11], [12]. This method has proven to be the most accurate and efficient technique for solving thin wire antenna and scattering problems.

Begin by entering the dipole length, the dipole radius, and the incidence and scattering angles. These angles are measured from the axis of the dipole, and have default values of 90° (broadside). Next enter the number of PWS expansion modes, and the mode number of the lumped-element load impedance. The default number of expansion modes is 3, and the default position of the lumped load is at the terminals of the middle expansion mode. Then enter the real and imaginary parts of the load impedance; the default values are zero. The resonant frequency of the dipole, the frequency step size, and the default number (7) of frequency points are displayed to the right of the **Compute** button. These values can be estimated by the routine by clicking the **Compute** button, or you can enter your own values for center frequency, frequency step size, and the number of frequency points. The geometry of the dipole may be viewed in three dimensions by clicking the **Show Geometry** button.

Upon clicking the **Compute** button, the routine will compute the moment method solution for the dipole, compute the RCS of the dipole over the specified frequency sweep, and list the results in dB per square meter, and in dB per square wavelength, in a list box. The scroll bar can be used to scroll through the data. After each computation, data is automatically written to a log file called WIRE.LOG, located in the PCAAD program directory. This data includes the frequency, wire radius, coordinates of all points on the wire structure, the definition of the PWS expansion modes, the moment method impedance matrix, and the voltage and current vectors.

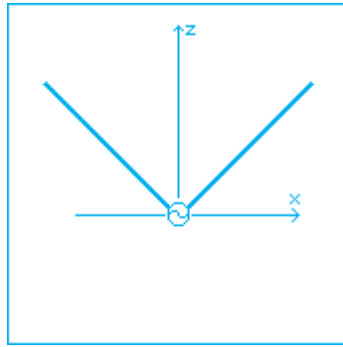
Validation

Consider a dipole 6.0 cm long with a radius of 0.002 cm. At 3 GHz, using three PWS expansion modes, the RCS was computed at broadside and compared with results from [11] for two values of load impedance:

Z_L	Reference [11]	PCAAD 6.0
0Ω	-22.0 dBsm	-21.9 dBsm
70Ω	-26.5 dBsm	-26.7 dBsm

Results were also compared with RCS data from [3]. The angle dependence of the routine was checked by verifying that the RCS of a short dipole dropped off by 6 dB when both the incidence and scattering angles were changed to 45° .

C.3. V-Dipole Antenna Analysis



This routine computes the input impedance, gain, and radiation pattern of a V-dipole antenna. The internal angle of the V-dipole is variable (an angle of 180° corresponds to a straight dipole). The feed point is at the apex of the wire arms. The solution uses the piecewise sinusoidal expansion (PWS) Galerkin method, with the exact exponential integral expressions used for the impedance matrix elements, as detailed in references [11]-[12]. This method has proven to be the most accurate and efficient

technique for solving thin wire antenna and scattering problems.

Begin by entering the dipole arm length, the dipole radius, the number of PWS expansion modes, and the internal angle of the dipole (between 2° and 180°). Because of symmetry, the number of PWS expansion modes must be odd. Pattern plots can be made in the E- and H-planes of the dipole, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button. The resonant frequency of the V-dipole, the frequency step size, and the default number (7) of frequency points are displayed to the right of the **Compute** button. These values can be estimated by the routine by clicking the **Compute** button, or you can enter your own values for center frequency, frequency step size, and the number of frequency points. The geometry of the V-dipole may be viewed in three dimensions by clicking the **Show Geometry** button.

Upon clicking the **Compute** button, the routine will compute the moment method solution for the V-dipole, and list the input impedance versus frequency in the list box. The scroll bar can be used to scroll through the data. The gain of the dipole at its beam maximum (along the z-axis), is computed at the center frequency of the frequency sweep. At this point you can plot the impedance characteristics versus frequency on a Smith chart plot or a VSWR/Return Loss plot, and can save the impedance data in a data file. The specified patterns are also calculated at the center frequency, and may be plotted using the **Plot Patterns** button, or saved to data files. After each computation, data is automatically written to a log file called WIRE.LOG, located in the PCAAD program directory. This data includes the frequency, wire radius, coordinates of all points on the wire structure, the definition of the PWS expansion modes, the moment method impedance matrix, and the voltage and current vectors.

Validation #1

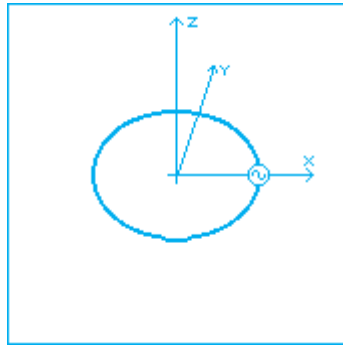
Consider a V-dipole antenna with arm lengths of 0.25λ , radius of 0.001λ , and variable angle. Calculated input impedance results from PCAAD are compared with data from [11], using one PWS expansion mode:

Angle	Reference [11]	PCAAD 6.0
90°	40.9 +j 9.0 Ω	40.1 +j 8.9 Ω
150°	69.3 +j 39. Ω	69.1 +j 38.9 Ω
180°	73.1 +j 42. Ω	73.1 +j 42.2 Ω

Validation #2

Consider a V-dipole with arm lengths of 1.5λ , and radius 0.001λ . From [2], the internal angle that results in maximum directivity is 82.5° . The resulting directivity from [2] is approximately 7.5 dB. Using 11 expansion modes, PCAAD gives a value of 7.8 dB.

C.4. Wire Loop Antenna Analysis



This routine computes the input impedance, gain, and radiation pattern of a wire loop antenna. The solution uses the piecewise sinusoidal expansion (PWS) Galerkin method, with the exact exponential integral expressions used for the impedance matrix elements, as detailed in references [11]-[12]. This method has proven to be the most accurate and efficient technique for solving thin wire antenna and scattering problems.

Begin by entering the radius of the loop, the wire radius, and the number of PWS expansion modes. Pattern plots can be made in the E- and H-planes of the dipole, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button. The resonant frequency of the loop, the frequency step size, and the default number (7) of frequency points are displayed to the right of the **Compute** button. These values can be estimated by the routine by clicking the **Compute** button, or you can enter your own values for center frequency, frequency step size, and the number of frequency points. The geometry of the loop antenna may be viewed in three dimensions by clicking the **Show Geometry** button.

Upon clicking the **Compute** button, the routine will compute the moment method solution for the loop, and list the input impedance versus frequency in the list box. The scroll bar can be used to scroll through the data. The gain of the loop at its beam maximum is computed at the center frequency of the frequency sweep (note that electrically small loops have a pattern null on axis, while larger loops have a beam maximum on the axis of the loop.) At this point you can plot the impedance characteristics versus frequency on a Smith chart plot or a VSWR/Return Loss plot, and can save the impedance data in a data file. The specified patterns are also calculated at the center frequency, and may be plotted using the **Plot Patterns** button, or saved to data files. After each computation, data is automatically written to a log file called WIRE.LOG, located in the PCAAD program directory. This data includes the frequency, wire radius, coordinates of all points on the wire structure, the definition of the PWS expansion modes, the moment method impedance matrix, and the voltage and current vectors.

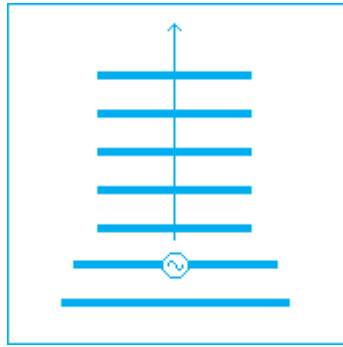
Validation

Consider a wire loop antenna with a wire radius of 0.001λ . The calculated input impedance from [11] is compared with results from PCAAD 6.0 for various loop radii and expansion modes. Note that using four expansion modes corresponds to a square loop, while eight modes corresponds to an octagonal loop, etc.

Loop Radius	PWS Modes	Zin Reference [11]	Zin PCAAD 6.0
0.0707λ	4	$44.8 + j 1589. \Omega$	$44.8 + j 1589. \Omega$
0.1592λ	4	$92.4 - j 300.9 \Omega$	$92.4 - j 300.9 \Omega$
0.1592λ	8	$109.7 - j 149.3 \Omega$	$109.7 - j 149.3 \Omega$
0.1592λ	16	$116.0 - j 109.1 \Omega$	$116.0 - j 109.1 \Omega$
0.1592λ	64	$117.5 - j 95. \Omega$	$117.5 - j 95.4 \Omega$

The directivity of a loop having a circumference of 1λ (radius = 0.1592λ) is about 3.4 dB [2]. PCAAD 6.0 gives a value of 3.3 – 3.5 dB, depending on the number of expansion modes used.

C.5. Yagi Dipole Array Analysis



This routine analyzes a Yagi-Uda dipole array using a moment method solution that includes all mutual coupling terms. Dipole currents are expanded using piecewise sinusoidal (PWS) modes, as described in references [11]-[12]. The routine computes input impedance, gain, front-to-back ratio, and patterns for the array. The array is assumed to have one reflector element, one driven dipole element, and an arbitrary number of director elements. The length and spacing for each element is variable, but the

radius is assumed to be the same for all elements.

Begin by entering the frequency, the dipole radius, the number of PWS modes on each dipole, and the number of director elements. Next, specify the lengths and spacings of the elements using the scroll bar and text boxes. The name of each element is listed in the box to the right of the scroll bar, followed by boxes for its length and spacing from the previous element. Thus, the spacing of the first element (the reflector) is not used, and is set to zero. Use the scroll bar to scroll through the elements to set or change lengths and spacings. Pattern plots can be made in the E- and H-planes of the dipole, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button.

When all data is entered, click the **Compute** button to calculate the moment method solution. The input impedance, gain, and front-to-back ratio will be listed. The specified patterns are also calculated, and may be plotted using the **Plot Patterns** button, or saved to data files. You may also save the moment method impedance matrix in a data file. The elements in this file are listed in row order for the top triangular half of the impedance matrix; the modes are numbered from bottom to top of each element, starting at the reflector. The geometry of the Yagi array may be viewed in three dimensions by clicking the **Show Geometry** button. After each computation, data is automatically written to a log file called WIRE.LOG, located in the PCAAD program directory. This data includes the frequency, wire radius, coordinates of all points on the wire structure, the definition of the PWS expansion modes, the moment method impedance matrix, and the voltage and current vectors.

Validation

Consider a Yagi array with the following specifications:

Reflector length	47.9 cm
Fed element length	45.3 cm
Director length (1)	45.1 cm
Spacing between reflector and feed	25.0 cm
Spacing between feed and director	25.0 cm
Dipole radius	0.25 cm
Frequency	0.30 GHz

This geometry is analyzed in [3], although the number of expansion modes is not stated. Running PCAAD 6.0 with 9 PWS modes per element (27 modes total) gives the following results:

Quantity	Reference [3]	PCAAD 6.0
Input impedance	$22 + j\,15\,\Omega$	$22 + j\,14\,\Omega$
Gain	9.4 dB	9.5 dB
Front-to-back ratio	5.6 dB	5.7 dB

The principal plane patterns of the Yagi array are shown below.

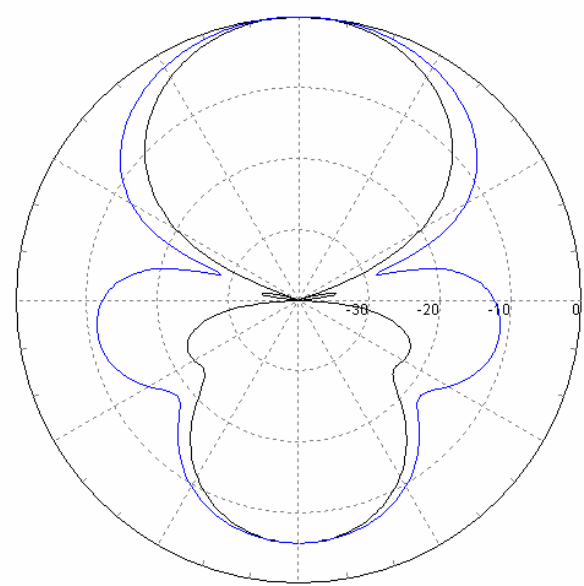
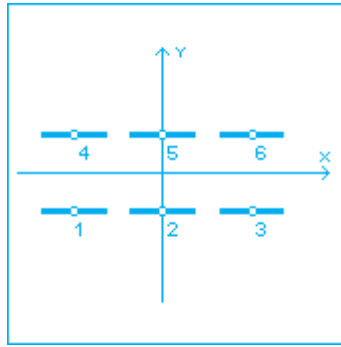


Figure 1. E-plane (black) and H-plane (blue) patterns of the Yagi array.

C.6. Finite Wire Dipole Array Analysis



This routine analyzes a finite planar wire dipole array using a moment method solution that includes all mutual coupling terms. Dipole currents are expanded using piecewise sinusoidal (PWS) modes, as described in references [11]-[12]. The routine computes input impedance at each dipole, array gain, and principle plane patterns for the array. The number and spacing of dipoles in each plane of the array is variable, but all dipoles are assumed to have the same length and radius. Each dipole

is center-fed with an arbitrary voltage generator, with a series generator impedance. As shown in the graphic, the dipoles are all parallel to the x -axis, and are numbered by rows along the x -axis.

Begin by entering the frequency, the number of dipoles in the x and y -directions, and the spacings (center-to-center) of the dipoles in the x and y -directions. Also enter the dipole length, the dipole radius, the number of PWS modes on each dipole, and the series generator resistance. The generator impedance is the same for all dipoles. Next, specify the generator voltage at each dipole using the scroll bar and boxes. The dipole index (numbered along the x -axis by rows) is listed in the box to the right of the scroll bar, followed by boxes for the generator voltage magnitude and phase (in degrees). Use the scroll bar to scroll through the elements to set or change generator voltages. Pattern plots can be made in the E- and H-planes of the dipole, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button.

When all data is entered, click the **Compute** button to calculate the moment method solution. The input impedance for each dipole will be listed in the box below the **Compute** button; use the scroll bar to scroll through the data. The input impedance is that seen looking into the dipole terminals, in contrast to the impedance seen from the generator (which would include the generator series impedance). The routine computes the gain of the array at the main beam position, assuming the main beam occurs in the plane where the patterns have been specified. The gain is computed in terms of the input power to the dipoles, and does not include power dissipated in the generator impedance. The logic here is that a realistic source will consist of a voltage generator and a series generator impedance, and the power dissipated in the source impedance should not be considered as a loss in the antenna itself. The specified patterns are also calculated at the center frequency, and may be plotted using the **Plot Patterns** button, or saved to data files. The geometry of the dipole

may be viewed in three dimensions by clicking the **Show Geometry** button. After each computation, data is automatically written to a log file called WIRE.LOG, located in the PCAAD program directory. This data includes the frequency, wire radius, coordinates of all points on the wire structure, the definition of the PWS expansion modes, the moment method impedance matrix, and the voltage and current vectors. The modes are counted from the left to the right of each element, along the E-plane rows of the array.

Validation

Consider a 12-element linear H-plane dipole array. The dipole length is 5 cm, the radius is 0.001 cm, the spacing between the elements is 5 cm, and the frequency is 3 GHz. The generator impedance is 0Ω , and the voltage sources are phased to scan the beam to -45° in the H-plane. Five PWS modes are used on each dipole. This geometry is the same as that treated on pp. 350-351 in reference [3]. Input impedance magnitudes from [3] are compared below with data computed from PCAAD 6.0:

Dipole	Generator Voltage	Z_{in} PCAAD 6.0	$ Z_{in} $ PCAAD 6.0	$ Z_{in} $ Ref. [3]
1	1.0/0°	107.1 +j 9.6 Ω	107.5 Ω	107.1 Ω
2	1.0/127°	97.8 +j 42.0 Ω	106.4 Ω	105.9 Ω
3	1.0/254°	91.0 +j 46.0 Ω	102.0 Ω	101.5 Ω
4	1.0/381°	87.8 +j 45.3 Ω	98.8 Ω	98.2 Ω
5	1.0/508°	86.4 +j 43.9 Ω	96.9 Ω	96.3 Ω
6	1.0/635°	85.9 +j 42.5 Ω	95.8 Ω	95.2 Ω
7	1.0/762°	86.1 +j 41.0 Ω	95.3 Ω	94.7 Ω
8	1.0/889°	87.5 +j 39.3 Ω	95.9 Ω	95.4 Ω
9	1.0/1016°	90.7 +j 38.9 Ω	98.7 Ω	98.2 Ω
10	1.0/1143°	95.0 +j 42.6 Ω	104.2 Ω	103.7 Ω
11	1.0/1270°	92.8 +j 55.2 Ω	108.0 Ω	107.3 Ω
12	1.0/1397°	57.4 +j 47.8 Ω	74.7 Ω	74.0 Ω

The H-plane pattern for this case is shown in Figure 2 below, and is in good agreement with the pattern in [3] (the pattern in [3] is scanned to 45° , while the PCAAD results are for an array scanned to -45° ; the difference can be attributed to a difference in numbering the dipoles.

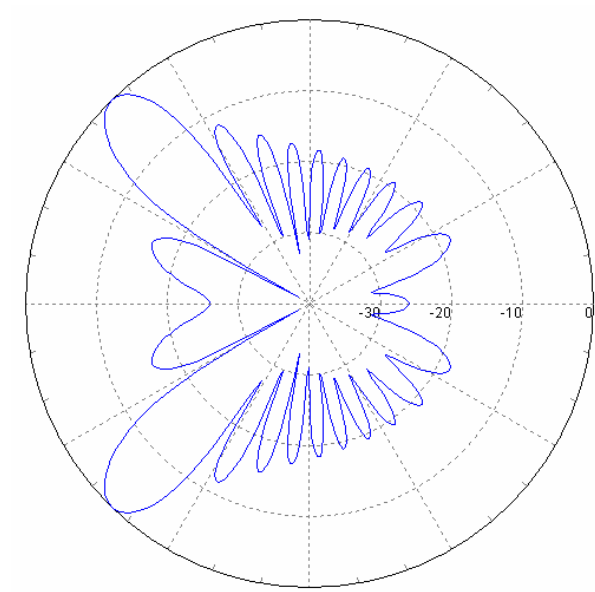
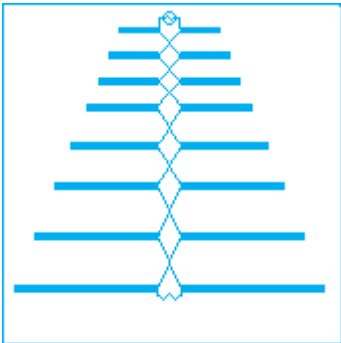


Figure 2. H-plane pattern of the dipole array.

C.7. Log Periodic Dipole Array Design



This routine gives an approximate design for a log-periodic dipole array, for a specified bandwidth and gain, based on the formulas given in reference [2], with corrections from reference [8]. The routine computes the necessary number of dipoles in the array, and the spacings, lengths, and radii for each element.

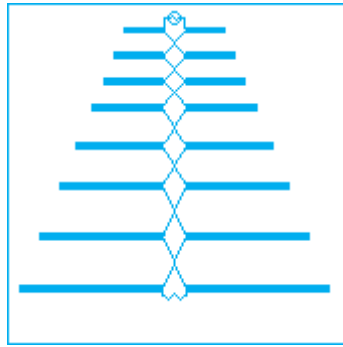
First enter the lower and upper frequencies of the desired operating band. Then enter the desired gain (between 7 and 11 dB), and the radius of the largest dipole. The routine prints out the log-periodic array scale factors, σ and τ , followed by a list of the spacing, length, and radius for each element in the array. The scroll bar in the list box can be used to scroll through the elements. Spacings are measured from the largest dipole; the last spacing is not

Validation

Consider an LPDA design with a lower frequency of 54 MHz, an upper frequency of 216 MHz, a directivity of 7.5 dB, and a largest dipole radius of 1 cm. This case is given in [1], with the following results:

Quantity	Reference [1]	PCAAD 6.0
σ	0.147	0.147
τ	0.822	0.822
First dipole length	264.8 cm	264.8 cm
Spacing to second dipole	77.8 cm	77.8 cm
Third dipole radius	0.64 cm	0.64 cm
Last dipole length	55.2 cm	55.2 cm

C.8. Log Periodic Dipole Array Analysis



This routine performs a complete analysis of a log-periodic dipole array using a moment method solution that includes all mutual coupling terms. Dipole currents are expanded using piecewise sinusoidal (PWS) modes, as described in references [11]-[12]. The array is fed with a transmission line having alternating terminals, and analyzed using port admittance matrices as described in reference [3]. The routine computes the input impedance at the feed port, the array directivity and gain, and the

patterns for the array. As shown in the graphic, the dipoles are all parallel to the x -axis, with the main beam in the z direction. The feed is assumed to be at the terminals of the smallest dipole, and a matched load is assumed to be located at the terminals of the largest dipole. The dimensions and spacings can be manually entered for each dipole, or you can enter the σ and τ parameters for the array and let the routine calculate all necessary dimensions. The geometry of the LPDA can be viewed in three dimensions by clicking the **Show Geometry** button.

Begin by entering the frequency, the feed line characteristic impedance, the number of dipoles in the array, and the number of expansion modes to be used on each dipole (this value may need to be increased for frequencies at the high end of the operating range). At this point you can click the **Get Data** button to enter the σ and τ parameters of the LPDA array, along with the length and radius of the first (longest) dipole in the array. The routine will then compute all necessary dimensions and spacings for the array, and automatically enter these values (upon clicking the **OK** button) into the scroll boxes. Alternatively, you can manually enter the length, spacing, and radius for each dipole in the array. The dipoles are numbered starting from the largest element; the last spacing value is not used. Pattern plots can be made in the E- and H-planes of the dipole, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button.

When all data is entered, click the **Compute** button to calculate the moment method solution. The input impedance, directivity, and gain (accounting for power lost in the termination resistor), and the front-to-back ratio are listed, along with the magnitude and phase of the terminal currents at each dipole (these values include the 180° reversal introduced by the feed line). This data can be used to observe how the "active region" moves along the array as frequency changes.

Validation

Consider a log periodic dipole array having 18 elements and $\sigma = 0.169$, $\tau = 0.917$, with the largest dipole having a length of 75 cm and radius of 0.3 cm. Assume a characteristic impedance of 83Ω . The table below compares the calculated input impedance and gain with values from [3]. Five expansion modes per dipole were used in the PCAAD solution.

Frequency (MHz)	Reference [3]		PCAAD 6.0	
	$Z_{in} (\Omega)$	Gain (dB)	$Z_{in} (\Omega)$	Gain (dB)
200	$69 - j 7$	8.8	$71 - j 6$	9.0
300	$72 - j 4$	9.4	$72 - j 3$	9.5
450	$76 - j 6$	9.5	$75 - j 8$	9.6
600	$78 - j 11$	9.4	$80 - j 12$	9.3

The figure below show the principal plane patterns for the array at 300 MHz.

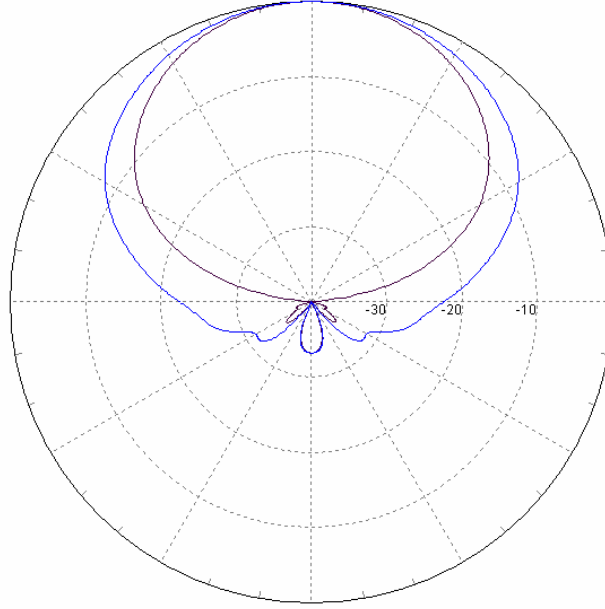
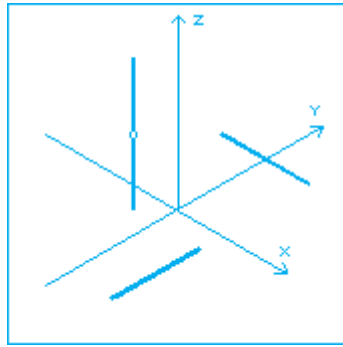


Figure 3. E-plane (black) and H-plane (blue) patterns of the LPDA array.

C.9. General Wire Antenna Analysis



This routine analyzes a general wire antenna geometry using a moment method solution that includes all mutual coupling terms. An arbitrary number of bent wire segments can be specified, with arbitrary positions, and voltage generators and lumped loads can be specified at the terminals of any expansion mode. The main limitation is that junctions between more than two wires are not allowed. All wires must also have the same radius. Wire currents are expanded using piecewise sinusoidal (PWS)

modes, as described in references [11]-[12]. The wire geometry is specified by defining a set of x , y , z coordinates to define the terminals of each PWS expansion mode on the wire structure. The geometry is specified in an ASCII data file (extension .ANT), with the following format (note: the format of this data file differs from that used in PCAAD 4.0):

FREQ, A	frequency (GHz), wire radius (cm)
NP	number of points on the wire structure
X, Y, Z	coordinates (in cm) of each point on the wire geometry (one row for each point)
NM	number of PWS expansion modes
I1, I2, I3	indices of the three coordinates that define each PWS mode
NPORTS	number of generator and/or load ports
PMODE, VGR, VGI, ZLR, ZLI	mode number of port, real and imaginary generator voltage, real and imaginary load impedance (one line for each port)

This data file can be created using a standard text editor; (see the DIPOLE.ANT, ARRAY.ANT, and YAGI.ANT files in the PCAAD program directory for examples of how the geometry files can be written). PWS modes are laid out along the wires starting from the first endpoint at point I1, to the terminals at point I2, and to the second endpoint at point I3. Note that each arm of a PWS expansion mode must be less than a quarter-wavelength long at the operating frequency. The routine computes the currents on the wires, the input impedance at each port, the directivity and gain of the antenna, the radiation efficiency, and the radiation patterns for the antenna.

The routine begins with a dialog box to enter a filename for the wire antenna geometry. The routine then lists some of the parameters of the wire geometry (number of points, number of expansion modes, and the number of feed ports) in

three text boxes - these can only be changed by changing the geometry data file. The routine also reads the operating frequency from the data file, but you may enter a different operating frequency, if desired. Because the polarization of an arbitrary wire antenna is not known, E-plane / H-plane patterns and Co-pol / X-pol patterns are not available for this routine, but E-theta and E-phi patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button. You may view the wire geometry in three dimensions by clicking the **Show Geometry** button. The perspective view may be rotated in elevation and azimuth using the scroll bars at the sides of the graph, and can be adjusted in size by using the zoom scroll bar.

Click the **Compute** button to begin computation of the moment method solution. When this calculation is complete, the gain, directivity, radiation efficiency, port impedances, and mode currents will be listed. The specified patterns are also calculated, and may be plotted using the **Plot Patterns** button, or saved to data files. After each computation, data is automatically written to a log file called WIRE.LOG, located in the PCAAD program directory. This data includes the frequency, wire radius, coordinates of all points on the wire structure, the definition of the PWS expansion modes, the moment method impedance matrix, and the voltage and current vectors.

As in the case of the planar dipole array, this routine computes the input impedance at each port as seen looking into the wire terminals, and does not directly include the series load impedance, if present. Similarly, the power dissipated in the antenna does not include power lost in the series generator impedances. If a port has a load impedance without a generator, however, the power lost in that load is included in the antenna loss. The logic here is that a realistic source will consist of a voltage generator and a series generator impedance, and the power dissipated in the source impedance should not be considered as a loss in the antenna itself. Lumped loads apart from the generators will, however, contribute to antenna loss. Thus an antenna with matched generators, but without separate lumped loads, will have an efficiency of 100%. An antenna having resistive lumped loads (e.g., a loaded dipole) will have an efficiency less than 100%.

Validation

The Yagi-Uda array example described in Section C.5. is used as a validation example for this routine, but with one expansion mode per element. The data file for this antenna is shown below (this file, YAGI.ANT, is supplied with PCAAD 5.0):

```
0.3, .25
9
-23.95, 0, 0
0, 0, 0
23.95, 0, 0
```

```

-22.65,0,25.
0.,0.,25.
22.65,0,25.
-22.55,0.,50.
0.,0.,50.
22.55,0.,50.
3
1,2,3
4,5,6
7,8,9
1
2,1.,0.,0.,0.

```

PCAAD 6.0 produced the following results:

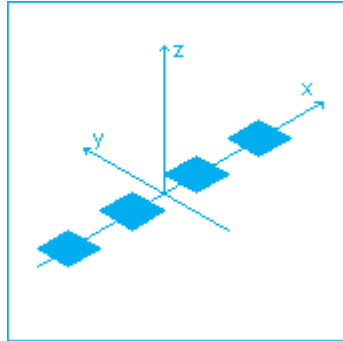
Input impedance	18.6 -j 3.0 Ω
Gain	9.5 dB
Front-to-back ratio	6.6 dB

These results agree with those obtained from the Yagi array routine with one expansion mode per element.

D. The Array Antennas Menu

This set of routines can be used to plot patterns for linear, rectangular planar, and circular planar arrays, to compute the input impedance of an infinite array of printed dipoles, and to plot a grating lobe diagram for planar arrays. Arrays of subarrays or elements with arbitrary patterns, and planar arrays with elements having arbitrary positions, can also be treated, and pattern synthesis can be performed for linear arrays using the Woodward-Lawson method. The array pattern routines are very flexible, allowing you to specify amplitude and phase variations, amplitude and phase errors, and the type of radiating element.

D.1. Uniform Linear Array Design and Analysis



This routine is used to plot patterns and compute directivity of a linear array antenna. You can specify array size, amplitude taper, phase distribution, and element type. Co-pol and cross-pol patterns can be calculated in an arbitrary elevation plane, and can be plotted either separately or together on a polar or rectangular pattern plot, or saved to data files. The routine can also be used to compute the directivity of the array. As indicated in the picture at the top left of the form, the array is

assumed to lie along the x -axis; if a ground plane is present (depending on the element type), it is positioned below the array parallel to the x - y plane. The pattern is computed using the array factor of the array multiplied by the element factor. Mutual coupling effects are not included in this routine. Directivity is computed by numerical integration of the pattern, which can be time consuming for large arrays. The maximum size of the array is limited to 200 elements. This routine uses three additional windows to select the array amplitude distribution, the array phase distribution, and the array element type. These windows are accessed by clicking the small **Select** button to the right of the appropriate text box for amplitude, phase, and element type.

Pattern plots can be made in the E- and H-planes of the array, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Note that E-plane / H-plane patterns are not available when the array elements are vertical monopoles. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button.

The **Array Amplitude Distribution** window allows you to choose from four commonly-used amplitude distributions, or to read amplitude data from a data file:

- **Uniform** uniform amplitude distribution
- **Chebyshev** Chebyshev amplitude taper for a specified sidelobe level
- **Taylor** Taylor amplitude taper for a specified sidelobe level and n-bar parameter
- **Cosine on a pedestal** cosine on a pedestal distribution of the form $C + (1 - C) \cos(\pi x / L)$
- **Data File** amplitude data is read from a specified data file

Select one of the five amplitude distribution options by clicking the appropriate button. For the Chebyshev distribution the desired sidelobe level must also be entered as a positive value in dB. The Chebyshev coefficients are computed using the highly accurate and efficient algorithm discussed in reference [19]. The Taylor distribution option requires sidelobe level as well as the n-bar parameter to be entered; the n-bar parameter must be in the range from 2 to 6. The Taylor coefficients are computed using the algorithm of reference [20], which is much more accurate and efficient for large arrays than the null-matching or aperture sampling techniques. The cosine-on-a-pedestal distribution requires entry of the pedestal height, C, in negative dB. Data read from an ASCII data file should be in absolute (not dB) voltage or current form (not power), with one line for each element in the array. If the size of the array is larger than the number of elements in the specified data file, the unspecified element amplitudes will be set to zero. The elements are counted by rows along the *x*-dimension, from left to right. You also have the option of adding gaussian distributed zero-mean random errors to any amplitude distribution. This is done by specifying the rms value (or standard deviation) of the errors in dB; specifying a value of zero rms error implies no amplitude error. Entering a new value for the rms error will cause the amplitude excitation to be re-computed, and updated in the list box. The excitation amplitudes for the array elements are shown in the list box in the amplitude distribution window, in absolute form (voltage or current amplitudes), and in dB. The scroll bar can be used to scroll through the list of excitations. You also have the option of saving the amplitude distribution to a data file, by clicking the **Save Data** button.

The **Array Phase Distribution** window allows you to choose the phase variation across the array from one of three options, or to read phase data from a data file.

- **Broadside Beam** phase set to zero on each element
- **Specify Scan Angle** progressive phase shift to steer beam to a specified scan angle
- **Specify Phase Shift** progressive phase shift applied
- **Data File** phase data is read from a specified data file

The **Specify Scan Angle** and **Specify Phase Shift** options require entry of the main beam scan angle, or the interelement phase shift, respectively. Specifying the scan angle for a linear array requires only the elevation angle, while the scan angle for a planar array requires both the elevation angle and the azimuth angle. Once a phase distribution has been selected, the routine will calculate the new set of excitation phases for the array elements, and display them in the list box. The scroll bar can be used to scroll through the list of excitation phases. These quantities will change when the frequency or element spacing is changed from the linear array window. Gaussian distributed zero-mean errors can also be added to the phase distribution by entering a non-zero value for the rms error (standard deviation). Entering a non-zero value causes the phase excitation to be modified, and updated in the list box. The phase excitation data can also be saved in an ASCII data file by clicking the **Save Data** button.

The **Array Element Selection** window allows you to select from one of five different element types, and to select the polarization of the element when possible:

- **Isotropic** ideal isotropic point source elements
- **Wire Dipole** thin wire dipole with or without a ground plane
- **Rectangular Waveguide** rectangular waveguide aperture in a ground plane
- **Circular Waveguide** circular waveguide aperture in a ground plane
- **Rectangular Microstrip Patch** rectangular microstrip patch elements
- **Circular Microstrip Patch** circular microstrip patch elements

Select the array element type by clicking the appropriate button. All but the isotropic element option requires entry of the element dimensions and polarization. The waveguide elements and the microstrip patch elements may be polarized in either the x direction (the plane of the array), or in the y direction (orthogonal to the plane of the array). The wire dipole may be polarized in the x , y , or z (vertical) direction, and may include a ground plane spaced a specified distance below the element. Specify no ground plane by setting the ground plane spacing to zero. The rectangular waveguide is assumed to have a TE_{10} mode distribution, while the circular waveguide is assumed to have a TE_{11} mode distribution. The patch elements are assumed to be operating in the dominant resonant mode.

Validation #1

We first consider the directivity of a single element computed from PCAAD and compared with data from the literature, for each of the possible element types:

Element	Literature	PCAAD 6.0
Isotropic	0.00 dB [2]	0.00 dB
Dipole ($L=\lambda/2$)	2.15 dB [2]	2.2 dB
Dipole, horizontal ($L=\lambda/20$, $\lambda/4$ above GP)	7.17 dB [2]	7.2 dB
Dipole, vertical ($L=\lambda/20$, $\lambda/4$ above GP)	6.63 dB [2]	6.6 dB
Rectangular aperture ($L=W=10\lambda$)	30.1 dB [2]	30.0 dB
Circular aperture (radius= 5λ)	29.2 dB [2]	29.1 dB
Rectangular patch ($L=0.328\lambda$, $W=0.219\lambda$)	7.0 dB [9]	7.1 dB
Circular patch (radius= 0.185λ)	7.1 dB [9]	7.1 dB

Validation #2

Consider a five element array of isotropic elements, with 0.4λ spacing, uniform amplitude, and phased to scan at 60° . Reference [3] gives the directivity as 7.0 dB; PCAAD 6.0 gives 7.1 dB.

Validation #3

Consider a 10 element broadside array of isotropic elements with a spacing of $\lambda/2$ and a 26 dB Chebyshev amplitude distribution. Element excitations from [2] are compared with results from PCAAD:

Element #	Reference [2]	PCAAD 6.0
1	0.357	0.361
2	0.485	0.489
3	0.706	0.711
4	0.890	0.895
5	1.000	1.000

The excitations for elements 6 through 10 are symmetric with these. The differences in the third decimal place in the above results can be attributed to round off error in the calculations in [2], as carrying through those calculations with five digit accuracy gives exact agreement with the results from PCAAD. The directivity from PCAAD is 9.5 dB, while in [2] an approximate result of 9.6 dB is given.

Validation #4

Consider a 10 element broadside array of isotropic elements with a spacing of 0.5λ and a 25 dB Taylor amplitude weighting with $n\text{-bar} = 2$. Element excitations from [20] are compared with results from PCAAD below. Excitations for elements 6 through 10 are symmetric with these.

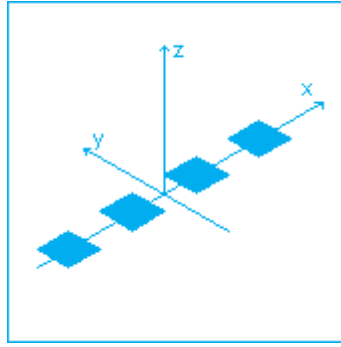
Element #	Reference [20]	PCAAD 6.0
1	0.417	0.417
2	0.528	0.528
3	0.709	0.709
4	0.889	0.889
5	1.000	1.000

Validation #5

Consider a 20 element broadside array of isotropic elements with a spacing of $\lambda/2$. If the elements are uniformly excited the directivity of this array is $D_0 = N = 20 = 13$ dB. If phase or amplitude errors are added to the excitations, the directivity will be reduced according to the formula, $D = D_0 / (1 + \sigma^2)$, where σ is the rms error. Running PCAAD for a rms phase error of 30° , or a rms amplitude error of 3 dB, and averaging over ten trials gives the following results:

Case	σ (rms error)	D (formula)	D PCAAD 6.0
no errors	0	13.0 dB	13.0 dB
phase errors	30°	11.9 dB	11.7 dB
amplitude errors	3 dB	12.3 dB	12.4 dB

D.2. Linear Subarray Design and Analysis



This routine is used to plot patterns of a linear array antenna composed of elements having an arbitrary element pattern defined by a data file. This is useful for analyzing arrays of subarrays, or arrays of elements that are not available through the element menu of the linear array routine. For example, this routine can be used to find patterns of an array of elements having a measured element pattern, an array of horn antennas, or an array of subarrays. You can specify array size (number of elements or

subarrays), the amplitude taper, and the phase distribution. The element spacing is measured between the centers of adjacent elements (or subarrays). The element pattern is specified only in the plane of the array, and assumed to be constant in the plane orthogonal to the array. For this reason the directivity may not be meaningful, and is not calculated. Without loss of generality, the polarization of the elements or subarrays is assumed to be along the x -axis. Pattern plots can be made in the E- and H-planes of the array, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button. As indicated in the picture at the top left of the form, the array is assumed to lie along the x -axis; if a ground plane is present (depending on the element type), it is positioned below the array parallel to the x - y plane. The pattern is computed using the array factor of the array multiplied by the subarray pattern. Mutual coupling effects are not included in this routine. The maximum size of the array is limited to 200 elements.

This routine uses two additional windows to select the array amplitude distribution, and the array phase distribution. The available amplitude and phase options are the same as those for the linear array module described in Section D.1., and are accessed by clicking the small **Select** button to the right of the appropriate text box for amplitude and phase. The selected amplitude and phase distributions can each be modified with gaussian distributed random errors, and can be saved as data files. The element pattern file is selected with a file dialog box. The element pattern data is assumed to be in the format of (angle in degrees, pattern in dB), with an angle range from -90 to 90° . The step size of the element data file is arbitrary – numerical interpolation is used when necessary. Pattern files generated by other PCAAD routines follow this format, allowing other PCAAD routines to be used to generate element patterns for direct use in this routine. For example, a horn antenna module can be used to generate a pattern file, which can then be used in this routine to find the pattern of an array of horns.

Validation

Consider an H-plane broadside array of 8 half-wave dipoles in free-space having a spacing of 0.6λ , and a uniform amplitude distribution. The pattern can be calculated using the linear array analysis routine, which gives a 3 dB beamwidth of 10.6° .

This same array can also be considered as a 4 element array, where each element now consists of a two-element H-plane subarray of two dipoles with a spacing of 0.6λ . The subarray pattern can be calculated using the linear array routine, and saved as a data file. This data file can then be used in the linear subarray routine, with $N = 4$ subarrays, and a spacing of 1.2λ between subarrays. The computed pattern and beamwidth agrees with the pattern obtained from the linear array routine. The pattern is shown below.

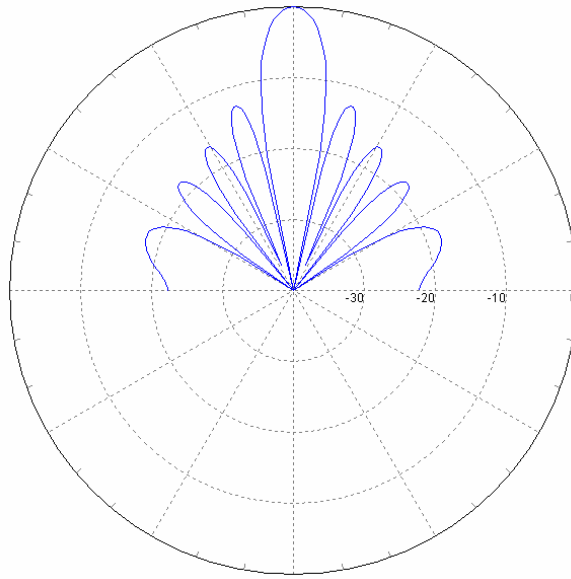
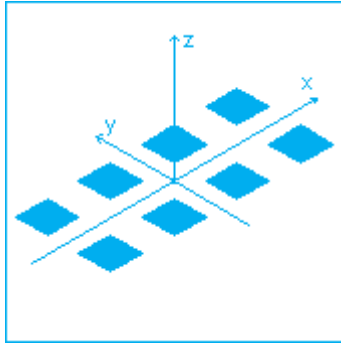


Figure 4. Pattern of an array consisting of four two-element H-plane dipole subarrays.

D.3. Uniform Rectangular Array Design and Analysis



This routine is used to plot patterns and compute the directivity of a rectangular planar array antenna. You can specify array size, amplitude taper, phase distribution, and element type. The number of elements and the element spacing (center-to-center) in each plane can be specified separately. Pattern plots can be made in the E- and H-planes of the array, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Note that E-plane / H-plane patterns are not available when the

array elements are vertical monopoles. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button. The directivity of the array can also be calculated. As indicated in the picture at the top left of the form, the array is assumed to lie in the x-y plane; if a ground plane is present (depending on the element type), it is positioned below the array parallel to the x-y plane. The pattern is computed using the array factor of the array multiplied by the element factor. Mutual coupling effects are not included in this routine. Directivity is computed by numerical integration of the pattern, which can be very time consuming for large arrays. The maximum size of the array is limited to 200 elements in each dimension.

As indicated in the picture at the top left of the form, the array is assumed to lie in the x-y plane; if a ground plane is present (depending on the element type), it is positioned below the array parallel to the x-y plane. The angle of the grid can be adjusted to treat arrays having either a rectangular or a triangular grid. The grid angle is 90° for a rectangular grid; for an equilateral triangular grid the grid angle is 60°, and the relation between the element spacings in the x and y directions is

$$d_y = d_x \sin \alpha = \frac{\sqrt{3}}{2} d_x .$$

The pattern is computed using the array factor of the array multiplied by the element factor. Mutual coupling is not included in this routine. Directivity is computed by numerical integration of the pattern, which can be very time consuming for large arrays. The maximum size of the array is limited to 200 elements in each dimension. Like the linear array routine, this routine uses three additional windows to select the **Array Amplitude Distribution**, the **Array Phase Distribution**, and the **Array Element Selection**. These three windows are described in Section D.1.

Validation #1

Consider a 2×2 broadside array of isotropic elements, with $\lambda/2$ spacings and uniform amplitude excitation. An exact expression for the directivity of broadside planar arrays of isotropic sources is given in [7]. This expression gives a directivity of 7.08 dB for this array; PCAAD gives 7.1 dB.

This routine was also validated by checking several special cases of single elements and linear arrays with the linear array routine. Planar array patterns were also checked for the correct scan angles and sidelobes.

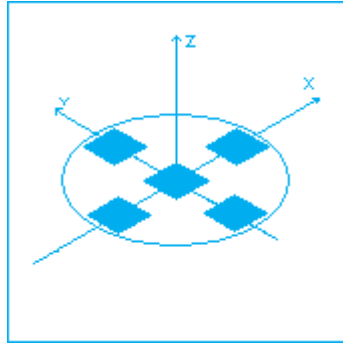
Validation #2

Consider a 4×4 planar array of x -polarized rectangular microstrip patches, with a triangular grid of 60° , a spacing in the x -direction of 0.5774λ , and a spacing in the y -direction of 0.5λ . The patch length and width are 0.3λ . PCAAD 6.0 gives the following results:

Quantity	PCAAD 6.0
3 dB beamwidth in $\phi=0^\circ$ plane	21.7°
3 dB beamwidth in $\phi=45^\circ$ plane	22.7°
3 dB beamwidth in $\phi=90^\circ$ plane	25.1°
Directivity	18.0 dB

These results should be similar to those obtained with an array using a rectangular grid and filling the same aperture area. For example, a patch array with a rectangular grid having 8 elements in the x -direction with a spacing of 0.289λ ($= 4 \times 0.5774\lambda/8$), and 4 elements in the y -direction with a spacing of 0.5λ , yields a directivity of 18.1 dB.

D.4. Uniform Circular Planar Array Design and Analysis



This routine is used to plot patterns and compute the directivity of a circular planar array. You can specify the radius of the array, element spacing (center-to-center), a radial amplitude taper, and the element type. The grid spacing of the elements is rectangular, and the routine calculates the number of elements that will approximately fit within a circular area of the specified radius. The amplitude taper is applied linearly (in dB) in the radial direction, assuming 0 dB at the center of the array, and an

edge taper as specified. The element type is selected by clicking the small **Select** button to the right of the text box for element type. Pattern plots can be made in the E- and H-planes of the array, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Note that E-plane / H-plane patterns are not available when the array elements are vertical monopoles. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button. The directivity of the array can also be calculated. As indicated in the picture at the top left of the form, the array is assumed to lie in the x-y plane; if a ground plane is present (depending on the element type), it is positioned below the array parallel to the x-y plane. The pattern is computed using the array factor of the array multiplied by the element factor. Mutual coupling effects are not included in this routine. Directivity is computed by numerical integration of the pattern, which can be very time consuming for large arrays. There is no limit to the maximum size of the array, but the directivity calculation will be unacceptably time consuming for more than about 100 elements.

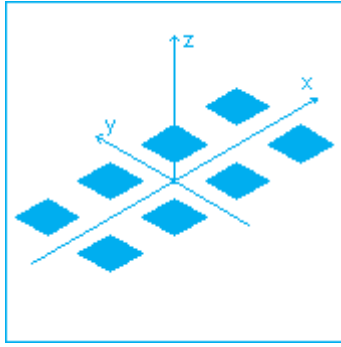
Validation #1

First consider a circular planar array with an outer radius of 1λ and an element spacing of 0.6λ , with isotropic elements. This results in a uniform rectangular grid of 3×3 elements, for which the circular array routine gives a directivity of 11.6 dB, and a half-power beamwidth of 30.6° . The rectangular planar array routine can be used for the same geometry, and gives identical results.

Validation #2

Next consider a circular planar array with an outer radius of 5λ and an element spacing of 0.5λ , with rectangular microstrip patches of size $0.3\lambda \times 0.3\lambda$. This results in an array of 317 elements. For a uniform amplitude distribution, PCAAD 6.0 gives a directivity of 30.1 dB for this array. Using the formula $D = 4\pi^2 R^2 / \lambda^2$ gives a value of 29.9 dB.

D.5. Arbitrary Planar Array Design and Analysis



This routine is used to plot patterns and compute directivity of a planar array of elements having arbitrary locations in the x - y plane, and arbitrary excitations. This can be useful for treating arrays that do not conform to the linear or planar apertures of the other array routines in PCAAD. A data file is used to specify element coordinates, excitation amplitude, and excitation phase. You can specify the element type from the same selection of elements available in the other array routines.

Pattern plots can be made in the E- and H-planes of the array, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Note that E-plane / H-plane patterns are not available when the array elements are vertical monopoles. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button. The directivity of the array can also be calculated. As indicated in the picture at the top left of the form, the array is assumed to lie in the x - y plane; if a ground plane is present (depending on the element type), it is positioned below the array parallel to the x - y plane. The pattern is computed using the array factor of the array multiplied by the element factor. Mutual coupling effects are not included in this routine. Directivity is computed by numerical integration of the pattern, which can be very time consuming for large arrays. The maximum size of the array is limited to 200 elements in each dimension.

The element data file is selected with a file dialog box. The data file should have the format of (x -coord in cm, y -coord in cm, amplitude, phase in degrees), with one line for each element. The amplitude data is in absolute voltage or current form (not in dB). The routine uses an additional window to select the array element type, accessed by clicking the small **Select** button to the right of the text box.

Validation

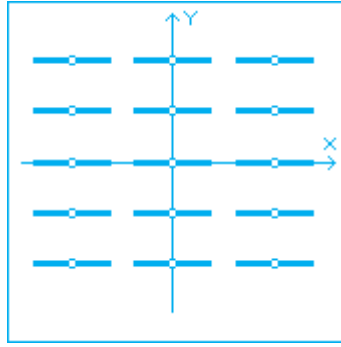
The 4×4 patch array with a triangular grid that was treated in **Validation #2** of Section D.3 was used here as well. The data file listing the element coordinates and excitations for this array is listed below (this file, ARRAY4X4.DAT, is supplied with PCAAD 6.0):

0.	0.0	1.0	0.0
0.5774	0.0	1.0	0.0
1.154	0.0	1.0	0.0
1.732	0.0	1.0	0.0
0.2887	0.5	1.0	0.0
0.8661	0.5	1.0	0.0

1.444	0.5	1.0	0.0
2.0209	0.5	1.0	0.0
0.	1.0	1.0	0.0
0.5774	1.0	1.0	0.0
1.154	1.0	1.0	0.0
1.732	1.0	1.0	0.0
0.2887	1.5	1.0	0.0
0.8661	1.5	1.0	0.0
1.444	1.5	1.0	0.0
2.0209	1.5	1.0	0.0

Results from this routine are in agreement with those obtained in Section D.3.

D.6. Infinite Printed Dipole Array Analysis



This routine computes the input impedance of an infinite array of dipole antennas printed on a grounded dielectric substrate using the full-wave solution described in reference [13]. It uses the exact Green's function for the dielectric substrate, and includes all mutual coupling effects. It can be used to treat dipoles in free-space above a ground plane by using a substrate dielectric constant of 1.0. The number of piecewise sinusoidal expansion modes on each dipole can also be chosen; this should be an odd

number since the dipoles are assumed to be center-fed. One to three modes is usually sufficient for accurate results.

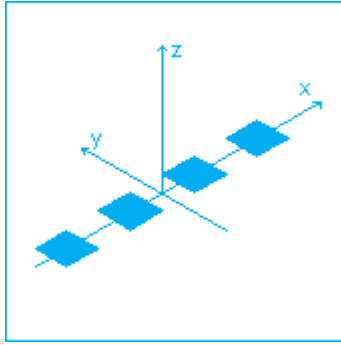
The required array parameters include the element spacings in the E and H planes, the dipole length and width, and the substrate thickness and dielectric constant. Input impedance data will be calculated for a fixed azimuth scan angle, and for elevation angles from zero to 90°. You must enter both the azimuth angle and the elevation step size. Since this is a full-wave calculation, it can be time consuming on slow computers, so it is helpful to not specify too small of a step size, to avoid unreasonably long run times. The input impedance at each elevation angle is listed in the list box as it is computed. Scroll through the list using the scroll bar. After the entire set of impedance data is calculated, you have the option of either saving the data to a data file, by clicking the **Save As** button, or plotting the impedance data on a Smith chart or a VSWR/Return Loss plot, by clicking the **Plot Impedance** button.

Validation

Consider an infinite array with an E- and H-plane spacing of 5 cm, a dipole length of 3.9 cm, a dipole width of 0.02 cm, and a substrate with a thickness of 1.9 cm and a dielectric constant of 2.55, and a frequency of 3 GHz. This example corresponds to the first case considered in [13]. For $\phi = 0$, with three expansion modes per dipole, we obtain the following results:

Theta	Zin - Reference [13]	Zin - PCAAD 6.0
0°	74.8 + j 2.7 Ω	74.8 + j 2.8 Ω
30°	73.3 + j 37.3 Ω	73.4 + j 37.3 Ω
60°	40.7 + j 1.9 Ω	40.7 + j 2.0 Ω
90°	0.10 + j 55.7 Ω	0.10 + j 55.7 Ω

D.7. Woodward-Lawson Linear Array Pattern Synthesis



This routine can be used to synthesize the pattern of a uniform linear array using the Woodward-Lawson method [2], [3]. You can specify array size, element spacing, and frequency. The pattern to be synthesized is specified in a scroll box at discrete pattern angles generated by the program. The amplitude and phase excitation for each element are computed, and listed in a scroll box. The array elements are assumed to be isotropic sources, with polarization along the x -axis. Pattern plots

can be made in the E- and H-planes of the array, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button. The pattern is computed using the array factor of the array; mutual coupling effects are not included in this routine. The pattern calculated in this routine is not normalized (other PCAAD routines normalize the maximum pattern value to 0 dB), in order to compare with the specified pattern values. For this reason, it may be necessary to adjust the maximum value of the pattern plot to view the entire pattern. The maximum size of the array is limited to 200 elements.

Begin by entering the operating frequency, the number of elements in the array, and the element spacing. The program will calculate discrete angles where the pattern will be sampled, and list these in the scroll box. The desired pattern value (in dB) can then be filled in the text box for each angle. Use the scroll bar to scroll through the set of samples. The routine will then compute the required amplitude and phase necessary to reproduce the desired pattern. A property of the Woodward-Lawson synthesis method is that it will provide a pattern that exactly matches the desired pattern at the sample angles, but will vary away from those angles.

Validation

Consider the synthesis of a sector pattern with an 11 element array having 0.5λ spacing. The sector pattern is defined as 0 dB between the angles of -45° and 45° , and -60 dB elsewhere. The following pattern values are entered at the sample points in the routine:

$\pm 65.4^\circ$	-60 dB
$\pm 46.7^\circ$	-60 dB
$\pm 33.1^\circ$	0 dB
$\pm 21.3^\circ$	0 dB
$\pm 10.5^\circ$	0 dB

0.0° 0 dB

The resulting synthesized pattern is plotted below. Note that the pattern values match those listed above.

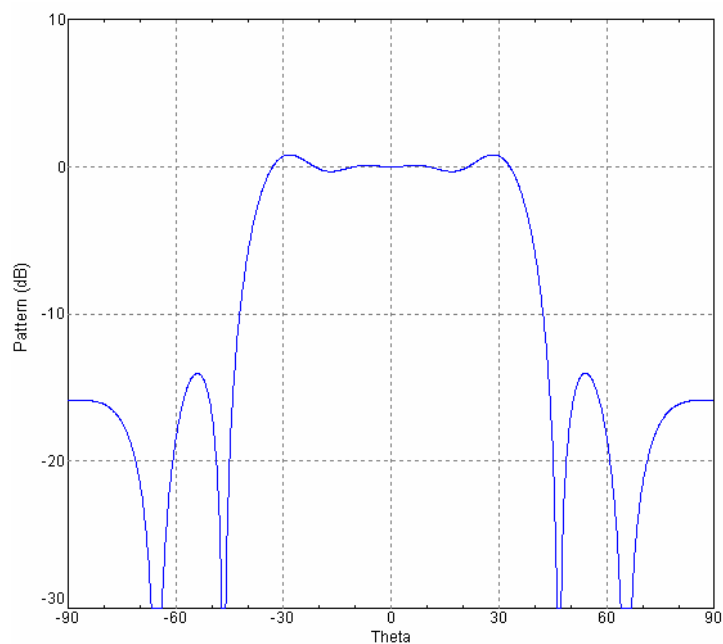
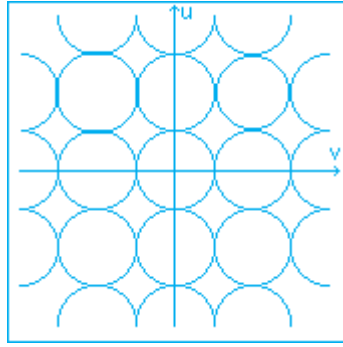


Figure 5. Synthesized sector pattern for an 11 element array.

D.8. Grating Lobe Diagram for a Planar Array



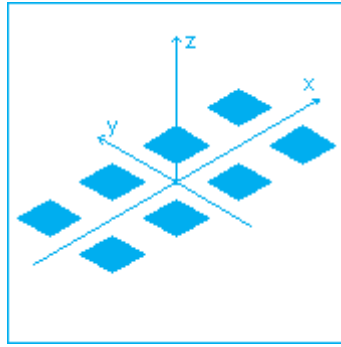
This routine plots a grating lobe diagram for a periodic planar array antenna, including the optional plotting of surface wave circles. A grating lobe diagram can be very helpful for determining the presence and location of grating lobes, and the movement of grating lobes with scan angle. In conjunction with surface wave circles, the grating lobe diagram can be used to predict the location of scan blindness angles in printed array antennas, as discussed in reference [13], or other arrays having a structure that supports guided waves. This routine provides a zoom control to adjust the size of u - v space that is plotted, and a convenient readout in u - v and theta-phi coordinates of the mouse cursor when it is positioned in the visible space region of the grating lobe diagram.

Begin by entering the array operating frequency, and the element spacings (center-to-center) in the horizontal and vertical directions. Next, enter the array grid angle. A grid angle of 90 degrees corresponds to a rectangular array, while a grid angle of 60 degrees corresponds to an array with a hexagonal grid. (For a hexagonal grid, the maximum element spacings with no grating lobes in visible space are 0.5774 wavelengths (horizontal), 0.5 wavelengths (vertical)). If you want to plot surface wave circles, enter a non-zero value for the normalized surface wave propagation constant; this can be computed using the **Surface Waves** routine under the **Transmission Lines** menu. Click the **Plot Circles** button to draw the grating lobe circles; the plot will automatically be updated if new data is entered, or if the zoom scroll bar is used. By default, the routine plots a segment of the $u = \sin \theta \cos \phi$, $v = \sin \theta \sin \phi$ plane from $-3 < u < 3$ and $-3 < v < 3$. The zoom scroll bar near the top of the window can be used to adjust this range. The visible space region of the grating lobe diagram occurs for $u^2 + v^2 < 1$, and is colored in light gray on the plot. The grating lobe circles are drawn in blue, and the surface wave circles are drawn as red circles. Moving the mouse cursor through the visible space region of the diagram will cause the readout box near the middle of the window to give a display of the cursor position in u - v space, as well as the corresponding theta-phi scan angle. In this way, you can easily determine the scan angle at which a grating lobe enters visible space, or the angle at which a scan blindness will occur. More accuracy can be obtained by zooming in on the visible space region by using the zoom scroll bar.

Validation

Consider an example from [13], for an array of printed dipoles with E- and H-plane spacings of $\lambda/2$, on a dielectric substrate with $\epsilon_r = 12.8$ and a thickness of 0.06λ . The array grid is rectangular. The PCAAD 6.0 **Surface Waves** routine gives a normalized surface wave propagation constant of 1.285816. Plotting the grating lobe diagram shows that no grating lobes will be present in visible space. Using the cursor to move to the intersection of a surface wave circle and the E-plane scan plane ($v = 0$) indicates a scan blindness will occur at 45° , in close agreement with the result of 46° from the full-wave solution in [13].

D.9. Effect of Array Excitation Errors and Failed Elements



The effect of random amplitude and phase errors on the pattern of an array is to raise the sidelobe level and decrease the gain. This routine computes the average sidelobe level and average loss in gain for an array having random amplitude and phase errors. The routine also includes the effect of failed elements in an array, and the quantization phase error and quantization lobe level due to phase shifter quantization. This routine is based on results given in [17] and [26].

Begin by entering the RMS amplitude error, in +dB, followed by the RMS phase error, in degrees. Each of these errors is assumed to have a normal distribution with zero mean. The phase error may be positive or negative. If desired, also enter the percentage of elements in the array considered to have failed (this value should be less than 100%). Click the **Compute** button to calculate the resulting average sidelobe level, and loss in gain, due to the entered errors and failed elements.

Note that the average sidelobe level is given relative to isotropic. The array directivity must be known to convert this value to a sidelobe level relative to the main beam of the array. For example, if the average sidelobe level due to errors is 5 dBi, and the error-free directivity of the array is 23 dB, then the sidelobe level relative to the main beam would be $5 - 23 = -18$ dB. Note that this is a residual sidelobe level caused by errors, in contrast to the design sidelobe level that is determined by the amplitude taper. The resulting sidelobe level will be the larger of these two levels. Thus, for the example above, if the array were designed for -13 dB sidelobes, the average error sidelobe level of -18 dB would probably not be noticeable. If, however, the array were designed for -25 dB sidelobes, the actual sidelobe level in the presence of errors would be in the range of -18 dB.

A separate frame is provide for phase shifter quantization effects. Use the list box to enter the number of bits for the phase shifters. Once a value is selected, the peak phase error (+/- degrees) will be displayed, along with the RMS phase error (+/- degrees). The RMS phase error value is also transferred to the phase error box in the excitation errors frame, for convenience. The level of the quantization lobe is also displayed – note that this value is given relative to the main beam of the array. The quantization lobe is due to the periodic phase error that is introduced when digital phase shifters are used in an array. This lobe is often higher than nearby sidelobes, especially when a small number of phase shifter bits are used. See [26] for techniques to reduce the effects of quantization lobes. Setting the phase shifter bits to **Off** turns off the phase shifter calculation functions.

Validation

The average sidelobe level due to amplitude and phase errors, relative to isotropic, is given by,

$$\overline{SLL}_i = \sigma_{\Delta}^2 + \sigma_{\phi}^2,$$

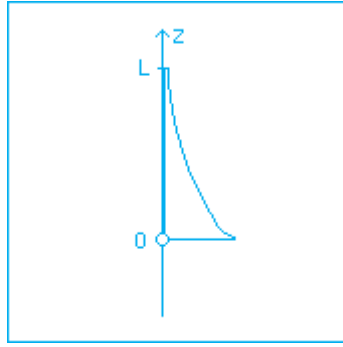
where $\sigma_{\Delta} = 10^{\sigma_{\Delta}(dB)/20} - 1$ is the rms amplitude error, and σ_{ϕ} is the rms phase error (in radians). Direct calculations shows that a 10° rms phase error leads to an average isotropic sidelobe level of -15.2 dB, and a 1.5 dB rms amplitude error leads to an average isotropic sidelobe level of -14.5 dB. PCAAD gives -15.2 dB, and -14.5 dB, respectively, for these two cases. If 50% of the array elements have failed, the gain is seen to be reduced by 3 dB, as expected.

E. The Aperture Antennas Menu

This set of routines are used for the analysis of various aperture antennas. Patterns and directivity can be calculated for line sources, rectangular and circular apertures, E and H-plane sectoral horns, pyramidal horns, conical horns, and corrugated horns. The waveguide horns are analyzed by the usual assumption of a waveguide field distribution in the aperture plane multiplied by a quadratic phase factor [2], [3]. For the sectoral and pyramidal horns this results in closed-form expressions for patterns and directivity in terms of Fresnel integrals. No such results are available for the conical or corrugated conical horns, so these cases are treated using a fairly efficient numerical integration technique. The aperture efficiency and directivity of prime focus parabolic antennas are characterized by assuming an idealized feed pattern of the $\cos^n \theta$ form [2]. Another routine uses numerical aperture integration to compute the secondary radiation patterns and directivity for prime focus reflectors with arbitrary feed patterns.

In PCAAD 6.0 the phase center is calculated for sectoral, pyramidal, corrugated pyramidal, diagonal, conical, and corrugated conical horn antennas using the derivative method with numerical integration of reference [29]. The phase center of an antenna is defined as the apparent center (along the axis of the main beam) of the circular far-zone phase fronts. For an ideal point source, the phase center is located at the point source. For small apertures with uniform phase, the phase center is located at the center of the aperture. For antennas with non-uniform phase, however, the phase center may be behind or in front of the aperture, and is generally different for different azimuthal planes. In many cases a unique phase center cannot be defined. The phase center location calculated in PCAAD may not be accurate for horns with very wide angles or very large phase errors

E.1. Traveling Wave Line Source Analysis



This routine calculates the pattern and directivity for a traveling wave electric line source antenna on the z -axis. Examples of such antennas include long wire antennas, dielectric rod antennas, electrically long slot antennas, and leaky wave antennas. The phase constant and attenuation constant can be specified, and the antenna can be fed at either the end or at the center of the line. A $\sin \theta$ element pattern factor can also be included, if desired. Patterns are computed using the

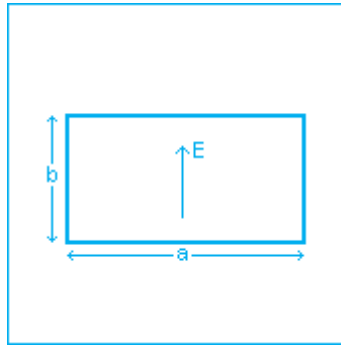
closed-form expressions found in reference [2]. Directivity is also calculated using closed-form expressions.

After entering the frequency, line source length, and phase and attenuation constants, click the **Compute** button to calculate the pattern and directivity. Pattern plots can be made in the E- and H-planes of the array, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button.

Validation

Consider a traveling wave end-fed wire antenna with a length of 5λ . The phase constant will be close to $360^\circ/\lambda$, and the attenuation may be neglected. Since this is a wire antenna, a $\sin \theta$ factor should be used. Reference [2] gives a beam maximum angle of 22.0° from the axis of the wire, in agreement with the pattern calculated by PCAAD. The free-space directivity from [2] is 10.7 dB, also in agreement with PCAAD.

E.2. Rectangular Aperture Antenna Analysis



This routine computes the patterns and directivity of a rectangular aperture antenna having a uniform phase distribution and either uniform or cosine tapered amplitude distributions in the E- and H-planes. The patterns are computed using closed-form expressions from References [2]-[3]. For accuracy for small apertures, the directivity is calculated by numerical integration when the aperture is smaller than 10 wavelengths on a side). For electrically large apertures the usual

directivity approximation of $4\pi A / \lambda^2$ (with the appropriate aperture efficiency) is used. The aperture is assumed to be located in an infinite ground plane, polarized in the y-direction, and the radiation is assumed to be one-sided. This analysis assumes an equivalent magnetic current only, and so does not include a $(1 + \cos \theta)$ obliquity factor, in contrast to the horn antenna analyses.

Begin by entering the frequency, and the E-plane and H-plane aperture dimensions. Then select the amplitude taper using the pull-down menu. You may choose to have either a uniform or a cosine taper in either of the two dimensions of the aperture (a TE₁₀ waveguide mode corresponds to uniform / cosine). Click the **Compute** button to compute the patterns and directivity. Pattern plots can be made in the E- and H-planes of the aperture, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button.

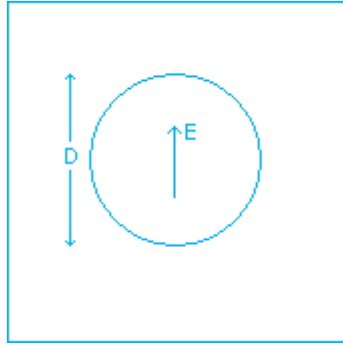
Validation #1

An open-ended X-band waveguide has an E-plane aperture dimension of 1.016 cm, and an H-plane aperture dimension of 2.286 cm. At 10 GHz, the linear array routine of PCAAD, with one waveguide element in the array, gives a directivity of 6.3 dB. The rectangular aperture routine, with a uniform amplitude taper in the E-plane and a cosine taper in the H-plane, gives a directivity of 6.3 dB.

Validation #2

A rectangular array of 24 x 24 microstrip patches, with lengths and widths of 0.3λ , element spacings of 0.5λ , and uniform amplitude and phase distributions, yields a directivity of 32.6 dB (using the PCAAD planar array routine). The rectangular aperture routine, for an aperture of $12\lambda \times 12\lambda$ with uniform amplitude tapers in both directions, gives a directivity of 32.6 dB.

E.3. Circular Aperture Antenna Analysis



This routine computes the patterns and directivity of a circular aperture antenna having a uniform phase distribution and either uniform or a parabolic tapered amplitude distributions in the radial plane. The patterns are computed using closed-form expressions from References [2]-[3]. For accuracy for small apertures, the directivity is calculated by numerical integration when the aperture is smaller than 10 wavelengths in diameter). For electrically large apertures the usual directivity approximation of

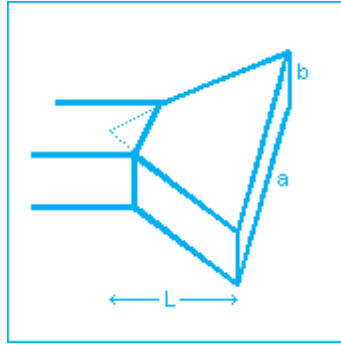
$4\pi A / \lambda^2$ (with the appropriate aperture efficiency) is used. The aperture is assumed to be located in an infinite ground plane, polarized in the y-direction, and the radiation is assumed to be one-sided. This analysis assumes an equivalent magnetic current only, and so does not include a $(1 + \cos \theta)$ obliquity factor, in contrast to the horn antenna analyses.

Begin by entering the frequency, and the aperture diameter. Then select the amplitude taper using the pull-down menu. You may choose to have either a uniform or a parabolic taper in the radial direction (the parabolic taper has a maximum at the center of the aperture, and is zero at the edge). Click the **Compute** button to compute the patterns and directivity. Pattern plots can be made in the E- and H-planes of the aperture, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button.

Validation

A circular planar array of diameter 10λ , with microstrip patches having lengths and widths of 0.3λ , element spacings of 0.5λ , and uniform amplitude and phase distributions, yields a directivity of 30.1 dB (using the PCAAD circular planar array routine). The circular aperture routine, for an aperture of 10λ diameter and a uniform amplitude taper, gives a directivity of 30.0 dB.

E.4. E- and H-plane Sectoral Horn Antenna Analysis



These two routines compute the patterns and directivity of E-plane or H-plane sectoral horn antennas, using closed-form expressions from reference [2]. The choice of E-plane or H-plane horn is made from the **Aperture** antenna menu. The directivity expression for the E-plane sectoral horn has been corrected according to reference [18]. The phase center, for both principal planes, is also computed.

Begin by entering the frequency, the E-plane aperture dimension, the H-plane aperture dimension, and the axial length of the horn. This length is the distance from the imaginary apex of the horn to the mouth of the horn (not the slant length). Also enter the increment for the pattern computation, then click the **Compute** button to compute the principle plane patterns. The routine prints out the maximum phase error at the edge of the aperture (relative to the center of the aperture), the optimum E-plane aperture dimension, the directivity of the horn, and the E- and H-plane phase centers. The optimum aperture dimension is the dimension that will result in maximum directivity for a horn of the same length. Pattern plots can be made in the E- and H-planes of the horn, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button.

Validation #1

Consider an E-plane sectoral horn at 3 GHz with an E-plane aperture dimension of 27.5 cm, an H-plane aperture dimension of 5 cm, and an axial length of 60 cm. Results for this example can be found in [2], and are compared with results from PCAAD below:

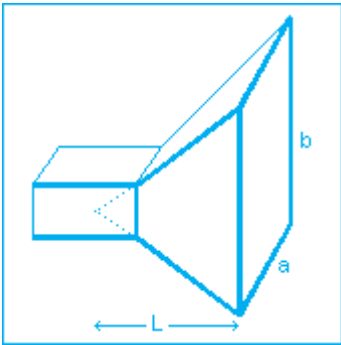
Quantity	Reference [2]	PCAAD 6.0
Max. phase error	56.7°	56.7°
Directivity	11.1 dB	11.1 dB
H-plane pattern at 60°	-5 dB (approx)	-4.1 dB

Validation #2

Consider an H-plane sectoral horn at 3 GHz with an E-plane aperture dimension of 2.5 cm, an H-plane aperture dimension of 55 cm, and an axial length of 60 cm. Results for this example can be found in [2], and are compared with results from PCAAD below:

Quantity	Reference [2]	PCAAD 6.0
Max. phase error	226.9°	226.9°
Directivity	8.76 dB	8.8 dB
E-plane pattern at 60°	-3.5 dB (approx)	-3.2 dB
H-plane pattern at 30°	-15 dB (approx)	-15.7 dB

E.5. Pyramidal and Corrugated Pyramidal Horn Analysis



These two routines compute the patterns and directivity of pyramidal and corrugated pyramidal horn antennas, using closed-form expressions from reference [2]. For horns with small apertures, accuracy is improved by computing the directivity by numerical integration of the pattern. The choice of pyramidal or corrugated pyramidal horn is made from the **Aperture** antenna menu. The phase center, for both principal planes, is also computed.

Begin by entering the frequency, the E and H-plane aperture dimensions, and the axial lengths of the horn in the E and H planes. The axial lengths are the distances from the imaginary apex of the horn in the E and H planes to the mouth of the horn (not the slant lengths). Click the **Compute** button to compute the patterns and related antenna parameters. The routine prints out the maximum phase errors at the edges of the aperture (relative to the center of the aperture), the optimum aperture dimensions, the directivity of the horn, and the E- and H-plane phase centers. Pattern plots can be made in the E- and H-planes of the horn, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button.

Validation #1

Consider a pyramidal horn at 3 GHz with an E-plane aperture dimension of 27.5 cm, an H-plane aperture dimension of 55 cm, and an axial length of 60 cm. Results for this example can be found in [2], and are compared with results from PCAAD below:

Quantity	Reference [2]	PCAAD 6.0
Max. phase error (E-plane)	56.7°	56.7°
Max. phase error (H-plane)	226.9°	226.9°
Directivity	18.8 dB	18.8 dB

Validation #2

Consider a pyramidal horn at 3.333 GHz with an E-plane aperture dimension 24 cm, an H-plane aperture dimension of 32.41 cm, an E-plane axial length of 40.41 cm, and an H-plane axial length of 44.59 cm. Reference [18] gives a directivity of 18.6 dB for this example; PCAAD gives 18.5 dB.

Validation #3

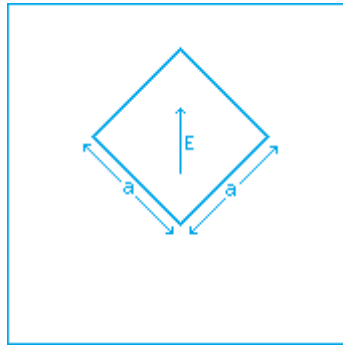
A standard gain horn has an E-plane aperture dimension of 8.3 cm, and H-plane aperture dimension of 10.2 cm, and E-plane axial length of 22.7 cm, and an H-plane axial length of 24.1 cm. At 24 GHz, the measured gain is 24.7 dB; PCAAD gives a directivity of 24.7 dB. Comparisons with other standard gain horns typically are in agreement to within about 0.1 dB.

Validation #4

A corrugated pyramidal horn has E- and H-plane aperture dimensions of 24.2 cm, and E- and H-plane axial lengths of 57.6 cm. Reference [22] provides measured 3 dB beamwidths versus frequency, along with independent calculations. This data is compared with results from PCAAD below:

Frequency (GHz)	Measured Beamwidth [22]	Calculated Beamwidth [22]	PCAAD Beamwidth
4.5	18°	19.3°	19.2°
6.0	15°	14.9°	14.8°
7.2	13°	12.8°	12.7°

E.6. Diagonal Horn Analysis



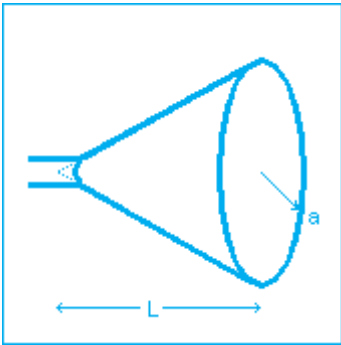
The diagonal horn antenna has a square aperture with the exciting electric field oriented along a diagonal axis. The main beam of the diagonal horn has circular symmetry, and the principal plane patterns have low sidelobes, with no cross-polarization. Further discussion of the diagonal horn antenna can be found in [28].

Begin by entering the frequency, the (square) aperture dimension, and the axial length of the horn. Click the **Compute** button to compute the patterns and related antenna parameters. The routine prints out the maximum phase error at the edge of the aperture (relative to the center of the aperture), the directivity of the horn, and the E- and H-plane phase centers (which are always identical). Pattern plots can be made in the E- and H-planes of the horn, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button.

Validation

A square diagonal horn with a width of 12.7 cm, and a very long length, is described in [28]. At 16.5 GHz the 3 dB beamwidth is given as 8.5° in both principal planes and the diagonal planes. PCAAD gives a 3 dB beamwidth of 8.3° . Reference [28] lists the aperture efficiency of the diagonal horn as 81% which, given the aperture area, yields a directivity of 27.0 dB. PCAAD gives 27.0 dB. The patterns show relatively high cross-polarization lobes of -15 dB in the diagonal planes.

E.7. Conical and Corrugated Conical Horn Analysis



These two routines compute the patterns and directivity of a conical (TE_{11} mode), or a corrugated conical (HE_{11} mode) horn antenna. The choice of conical or corrugated horn is made from the **Aperture** antenna menu. The principle plane patterns are computed using an efficient numerical integration algorithm that includes the quadratic phase error term. The phase center, for both principal planes, is also computed.

Begin by entering the frequency, the aperture radius, and the axial length of the horn. This length is the distance from the imaginary apex of the horn to the mouth of the horn (not the slant length). Click the **Compute** button to compute the patterns and related antenna parameters. The routine prints out the maximum phase error at the edge of the aperture (relative to the center of the aperture), and the directivity of the horn. Pattern plots can be made in the E- and H-planes of the horn, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button.

Validation #1

Consider a conical horn at 5 GHz with an aperture radius of 12 cm and an axial length of 48.6 cm. Results from reference [5] are compared with PCAAD:

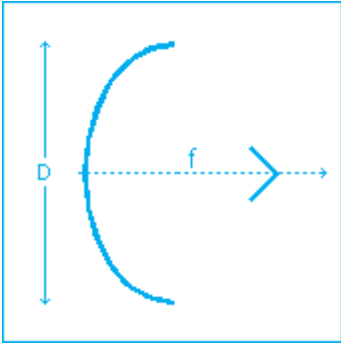
Quantity	Reference [5]	PCAAD 6.0
Max. phase error	86.4°	88.9°
Directivity	20.4 dB	20.3 dB
E-plane pattern at 20°	-13.4 dB	-12.9 dB
H-plane pattern at 20°	-15.0 dB	-14.8 dB

Validation #2

Consider a corrugated conical horn at 5 GHz with an aperture radius of 12 cm and an axial length of 48.6 cm. Results from reference [5] are compared with PCAAD:

Quantity	Reference [5]	PCAAD 6.0
Max. phase error	86.4°	88.9°
Directivity	19.9 dB	19.4 dB
E-plane pattern at 17.5°	-10 dB	-9.9 dB
H-plane pattern at 17.5°	-10 dB	-10.3 dB

E.8. Approximate Parabolic Reflector Analysis



This routine analyzes the performance of a prime-focus parabolic reflector antenna, under the assumption that the feed antenna has a rotationally symmetric power pattern that can be approximated as $\cos^n \theta$. In this case, simple (but exact) expressions can be obtained for the spillover and taper efficiencies, as discussed in reference [2]. The effect of surface roughness can also be included.

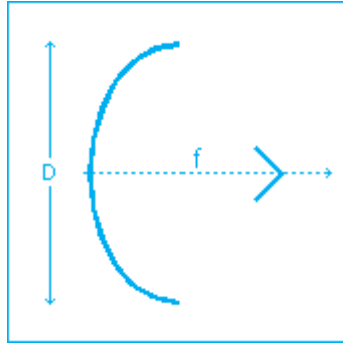
Begin by entering the frequency, the f/D ratio, the dish diameter, and the rms surface roughness. The surface roughness dimension has a default value of zero. Next, specify the feed pattern in one of three forms: enter either the 3 dB beamwidth, the 10 dB beamwidth, or the actual value of $n = 2, 4, 6$, or 8 for a pattern of the form $\cos^n \theta$. If you specify a beamwidth, the routine will calculate the closest value of n that approximates this beamwidth, and will display the value of n that it will use. The routine then computes the spillover, taper, roughness, and total aperture efficiencies, then computes the directivity of the antenna. The 3 dB beamwidth is also calculated from the directivity.

Validation

Consider a parabolic reflector with a dish diameter of 1000 cm, an f/D ratio of 0.5, a feed pattern with $n = 2$, and no surface roughness, operating at 3 GHz. This example is considered in [2], and compared with PCAAD below:

Quantity	Reference [2]	PCAAD 5.0
Spillover efficiency	0.784	0.784
Taper efficiency	0.957	0.957
Aperture efficiency	0.750	0.751
Directivity	48.7 dB	48.7 dB

E.9. Parabolic Reflector Pattern Analysis



This routine computes the patterns of a prime-focus parabolic reflector antenna by numerical aperture integration as outlined in references [2]-[3]. The feed is specified with two data files for the E- and H-plane patterns; these may be generated through other PCAAD antenna routines. The aperture efficiency and directivity are also computed, by numerical integration. The effect of surface roughness can also be included.

Begin by entering the frequency, the f/D ratio, the dish diameter, and the rms surface roughness. The surface roughness dimension has a default value of zero. Next, select the feed pattern files using the file dialog boxes. The feed pattern data must be in the format of (angle in degrees, pattern in dB), with an angle range that extends at least from -90° to 90° . The step size of the feed pattern data file is arbitrary – numerical interpolation is used when necessary. Pattern files generated by other PCAAD routines follow this format, allowing other PCAAD routines to be used to generate feed patterns for direct use in this routine. For example, a horn antenna module can be used to generate a feed pattern file, which can then be used in this routine to find the secondary patterns of the reflector. Only the feed pattern amplitude is used. The feed is assumed to be linearly polarized at $\phi=0^\circ$.

Select the pattern type and parameters with the **Pattern Type Select** button. Pattern plots can be made in the E- and H-planes of the reflector, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. 3-D volumetric patterns are not available because the beamwidth of most reflectors is too narrow to be plotted in volumetric form. Since most reflector antennas have narrow beamwidths, the elevation step size should be small, typically between 0.01 degrees and 0.1 degrees. Also specify the maximum angular range of the elevation pattern plot. Because of the narrow beamwidth of most reflector antennas, the maximum angular range of the pattern calculation usually does not need to exceed a few degrees. Since numerical aperture integration can be time consuming for an electrically large antenna, computer time may be excessive if the maximum angular range is too large, or the step size is too small.

Validation #1

Consider a reflector antenna with a diameter of 100λ , $f/D = 0.5$, and a feed having a power pattern of $\cos^2 \theta$ in both planes. This pattern can be obtained as the E-plane pattern of a short dipole along the x-axis, as computed using the linear array routine with one dipole element. Exact results can be obtained from the previous reflector

analysis routine with $n = 2$. The following results are obtained:

Quantity	PCAAD (exact)	PCAAD (numerical)
aperture efficiency	75%	75%
directivity	48.7 dB	48.7 dB
3 dB beamwidth	0.67°	0.63°

Validation #2

A prime-focus reflector has a diameter of 100 cm, $f/D = 0.5$, and operates at 30 GHz. The feed is a short dipole, with an E-plane pattern of $\cos \theta$, and an H-plane pattern that is constant (these data files, named paraE.dat and paraH.dat, are supplied with PCAAD). The calculated pattern in the $\phi=45^\circ$ plane is presented in reference [3], showing a maximum cross-pol level of 26 dB and a maximum sidelobe level of 20 dB. The calculated patterns from PCAAD are shown below, with results in agreement with these values.

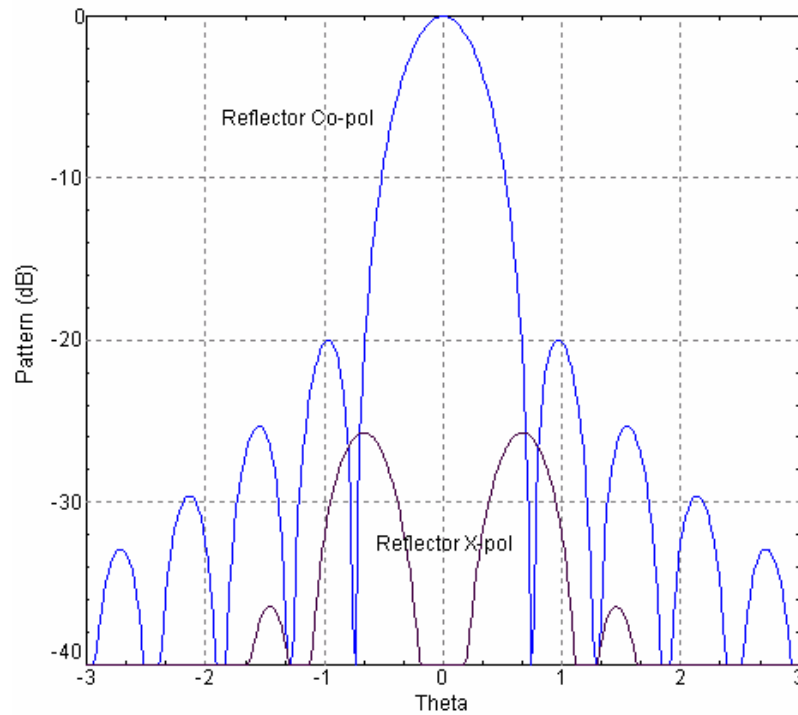
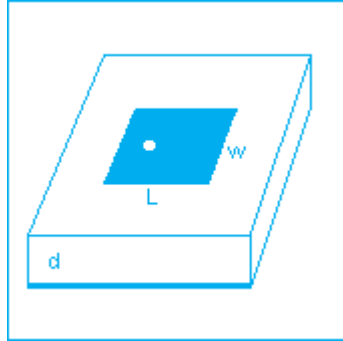


Figure 6. Calculated co-pol (blue) and cross-pol (black) patterns for the parabolic reflector antenna in the $\phi=45^\circ$ plane.

F. The Microstrip Antennas Menu

This set of six routines implement cavity model solutions for rectangular and circular microstrip antennas. Two different solutions are available for probe-fed rectangular patches, as well as solutions for a microstrip line fed rectangular patch, a proximity coupled rectangular patch, an aperture coupled rectangular patch, and a probe-fed circular patch. In general, cavity model solutions work well for microstrip antennas on thin substrates, but fail for substrates thicker than about 0.02λ . Subject to this limitation, these routines can be used to get a reasonably good estimate of the resonant frequency and input impedance for these antennas, but be aware that these routines will not be as accurate as full-wave solutions. Use of the integrated Smith chart routine gives quick results for microstrip antenna designs. The routines also compute patterns and directivity.

F.1. Rectangular Probe-Fed Patch Analysis (Carver model)



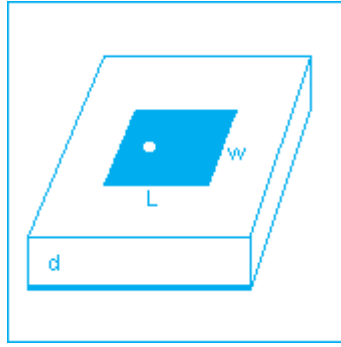
This routine analyzes a rectangular probe-fed microstrip antenna using Carver's transmission line model discussed in references [6] and [14]. It treats the patch as a transmission line with equivalent end admittances to account for radiation, and length extensions are used to account for fringing fields at the radiating edges. The radiation patterns are found from the equivalent magnetic currents for the dominant TM_{10} mode at the edges of the patch, including the sidewall contributions. The sidewall currents

do not contribute to the principal plane patterns, but do have an effect on cross-pol fields and the directivity, which is calculated by integrating the far-field patterns. This solution generally gives good results for microstrip antennas on thin substrates with low dielectric constants.

Enter the patch length (in the resonant direction), the patch width, the dielectric constant, the substrate thickness, the dielectric loss tangent, and the distance of the probe from the radiating edge of the patch. The routine will then compute the approximate resonant frequency, the input resistance, the approximate bandwidth, the radiation efficiency, and the directivity. Pattern plots can be made in the E- and H-planes of the patch, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with **the Pattern Type Select** button.

See the following section for validation examples.

F.2. Rectangular Probe-Fed Patch Analysis (cavity model)



This routine analyzes a rectangular probe-fed microstrip antenna using a cavity model similar to that discussed in reference [8]. The patch is treated as a lossy cavity to account for radiation, and length extensions are used to account for fringing fields at the radiating edges. A parallel RLC equivalent circuit is then used to compute the input impedance versus frequency. The radiation patterns are found from the equivalent magnetic currents for the dominant TM_{10} mode at the edges of the patch. The directivity is

calculated by integrating the far-field patterns. This solution generally gives good results for microstrip antennas on thin substrates with low dielectric constants.

Enter the patch length (in the resonant direction), the patch width, the dielectric constant, the substrate thickness, the dielectric loss tangent, and the distance of the probe from the radiating edge of the patch (the probe is assumed to be centered along the width dimension). The routine will then estimate the resonant frequency of the antenna, and suggest a frequency step size. These values are displayed, along with the default number of frequency points, in three boxes to the right of the **Compute** button. Click the **Compute** button to accept these values for the frequency sweep, or enter new values for the sweep center frequency, the frequency step size, or the number of frequency points. The routine will then compute the input impedance of the antenna over this frequency sweep, and display the results in the list box. If necessary, use the scroll bar at the right of the box to scroll through the list of impedances. The routine also computes the approximate bandwidth, the radiation efficiency, and the directivity of the antenna.

At this point you can plot the impedance locus versus frequency on a Smith chart plot or a VSWR/Return Loss plot, and can save the impedance data in a data file. Pattern plots can be made in the E- and H-planes of the patch, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button.

Validation #1

Consider a rectangular probe-fed patch with a length of 4.92 cm, a width of 3.28 cm, a substrate with a dielectric constant of 2.32 and a thickness of 0.159 cm, and a feed probe positioned 1.0 cm from the edge of the patch. This example is given in reference [9], with the following results compared with Carver's model and the cavity model from PCAAD:

Quantity	Reference [9]	Carver Model	Cavity Model
Resonant frequency	2.0 GHz	1.94 GHz	1.97 GHz
Resonant resistance	?	336 Ω	192 Ω
Bandwidth	0.7 %	1.2 %	1.7 %
E-plane beamwidth	102°	103°	101°
H-plane beamwidth	85°	86°	86°
Directivity	7.0 dB	7.0 dB	7.0 dB

Validation #2

Consider a probe-fed rectangular patch with a length of 1.8 cm, a width of 2.505 cm, a substrate with a dielectric constant of 2.2 and a thickness of 0.159 cm. The probe is positioned 0.5 cm from the edge of the patch. Results from the cavity model of PCAAD are plotted on the Smith chart below, and compared with measured data. Agreement is very good, particularly near resonance.

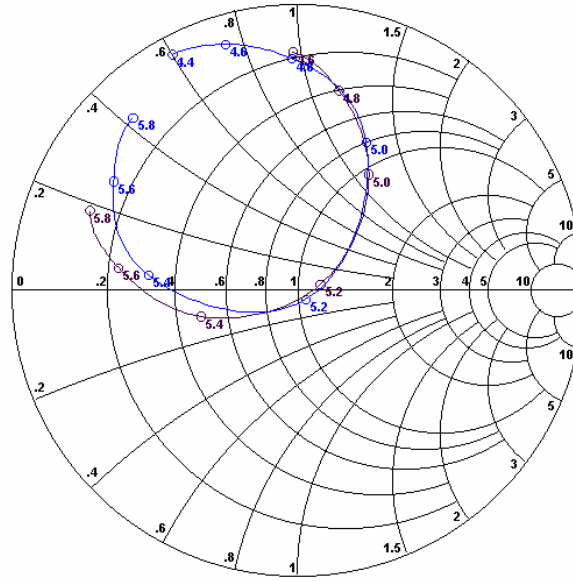
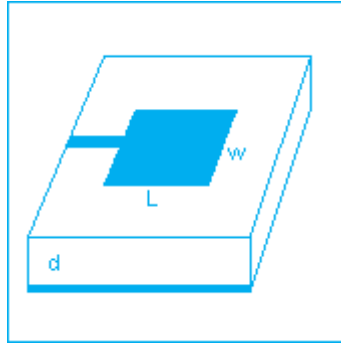


Figure 7. Smith chart plot of calculated (black) and measured (blue) data for a probe-fed rectangular microstrip antenna.

F.3. Rectangular Line-Fed Patch Analysis



This routine analyzes a rectangular microstrip line-fed microstrip antenna using the transmission line model discussed in reference [9]. The patch is treated as a transmission line with equivalent end admittances to account for radiation, and length extensions are used to account for fringing fields at the radiating edges. The transmission line circuit is used to compute input impedance versus frequency. The radiation patterns are found from the equivalent magnetic currents for the dominant TM_{10} mode

at the edges of the patch. The directivity is calculated by integrating the far-field patterns. This solution has been validated for a large number of practical designs, and generally gives good results for microstrip antennas on thin substrates with low dielectric constants.

Enter the patch length (in the resonant direction), the patch width, the dielectric constant, the substrate thickness, the dielectric loss tangent, and the width of the microstrip feed line. The routine will compute and display the required feed line width for a 50Ω line; enter a new value if your line width is different. The routine will then estimate the resonant frequency of the antenna, and suggest a frequency step size. These values are displayed, along with the default number of frequency points, in three boxes to the right of the **Compute** button. Click the **Compute** button to accept these values for the frequency sweep, or enter new values for the sweep center frequency, the frequency step size, or the number of frequency points. The routine will then compute the input impedance of the antenna over this frequency sweep, and display the results in the list box. If necessary, use the scroll bar at the right of the box to scroll through the list of impedances. The routine also computes the approximate bandwidth, the radiation efficiency, and the directivity of the antenna.

At this point you can plot the impedance locus versus frequency on a Smith chart plot or a VSWR/Return Loss plot, and can save the impedance data in a data file. Pattern plots can be made in the E- and H-planes of the patch, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button.

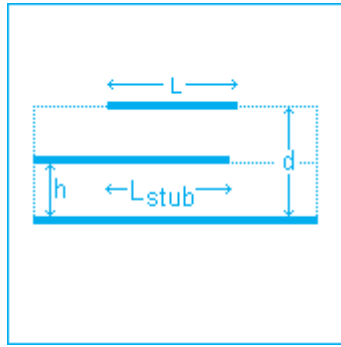
Validation

Consider a rectangular microstrip line fed microstrip antenna with a patch length of 3.315 cm, a patch width of 3.317 cm, a dielectric constant of 2.2, a substrate

thickness of 0.079 cm, a loss tangent of 0.001, and a feed line width of 0.47 cm. Measured results from [9] are compared with PCAAD:

Quantity	Measured [9]	PCAAD 6.0
Resonant frequency	3.00 GHz	3.01 GHz
Resonant resistance	278 Ω	241 Ω
Bandwidth	1.1 %	1.1 %

F.4. Rectangular Proximity-Coupled Patch Analysis



This routine analyzes a rectangular proximity-coupled microstrip antenna using a transmission line model discussed in references [9], [16], [21]. The patch is treated as a transmission line with equivalent end admittances to account for radiation, and length extensions are used to account for fringing fields at the radiating edges. The reciprocity method is used to compute the coupling term between the feed line and the edge of the patch, and the transmission line circuit is used to compute input impedance

versus frequency. The radiation patterns are found from the equivalent magnetic currents for the dominant TM_{10} mode at the edges of the patch. The directivity is calculated by integrating the far-field patterns. This solution is not highly accurate, but generally gives reasonable results for microstrip antennas on thin substrates with low dielectric constants.

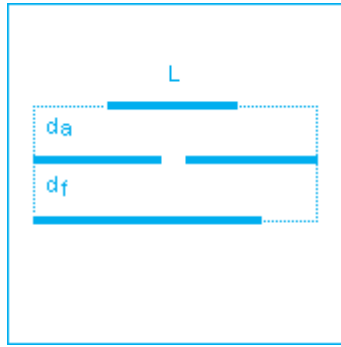
Enter the patch length (in the resonant direction), the patch width, the total substrate thickness (d), the dielectric constant, and the height (h) of the feed line above the ground plane (this must be less than the substrate thickness). Next enter the width of the microstrip feed line, and the loss tangent of the substrate material. Finally, enter the stub length, as measured from the edge of the patch to the end of the stub. The routine will then estimate the resonant frequency of the antenna, and suggest a frequency step size. These values are displayed, along with the default number of frequency points, in three boxes to the right of the **Compute** button. Click the **Compute** button to accept these values for the frequency sweep, or enter new values for the sweep center frequency, the frequency step size, or the number of frequency points. The routine will then compute the input impedance of the antenna over this frequency sweep, and display the results in the list box. If necessary, use the scroll bar at the right of the box to scroll through the list of impedances. The routine also computes the approximate bandwidth, the radiation efficiency, and the directivity of the antenna.

At this point you can plot the impedance locus versus frequency on a Smith chart plot or a VSWR/Return Loss plot, and can save the impedance data in a data file. Pattern plots can be made in the E- and H-planes of the patch, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button.

Validation

Consider a proximity-coupled patch with a length of 2.5 cm, a width of 4.0 cm, and a substrate with a dielectric constant of 2.2 and a thickness of 0.316 cm. The feed height is 0.158 cm, and the feed line width is 0.5 cm. The length of the stub is 1.25 cm. At 3.6 GHz, PCAAD gives an input impedance of $34 - j 3 \Omega$, while measured data from [6] gives an impedance of about $40 + j 3 \Omega$.

F.5. Rectangular Aperture Coupled Patch Analysis



This routine analyzes a rectangular aperture coupled microstrip antenna [15], using a cavity model solution for the patch combined with the reciprocity method [16] for treating the slot feed and microstrip line. The patch is modeled as a lossy cavity with magnetic sidewalls, and the Q is found by integrating the radiated fields of the patch. Length extensions are used to account for fringing fields at the radiating edges of the patch, and closed-form approximations for short slots are used for the slot self-conductance and

susceptance. The radiation patterns are found from the equivalent magnetic currents for the dominant TM_{10} mode at the edges of the patch. The directivity is calculated by integrating the far-field patterns. It is assumed that the coupling slot is centered under the patch, the feed line is centered across the slot, and that the feed line is terminated with an open-circuited stub.

First enter the parameters for the patch side of the antenna geometry: the substrate thickness, dielectric constant, patch length (resonant dimension), patch width, slot length (long dimension), and slot width (short dimension). Then enter the parameters for the feed side of the antenna: the substrate thickness, dielectric constant, feed line width, and tuning stub length (measured from the center of the slot to the end of the stub). The routine will then estimate the resonant frequency of the antenna, and suggest a frequency step size. These values are displayed, along with the default number of frequency points, in three boxes to the right of the **Compute** button. Click the **Compute** button to accept these values for the frequency sweep, or enter new values for the sweep center frequency, the frequency step size, or the number of frequency points. The routine will then compute the input impedance of the antenna over this frequency sweep, and display the results in the list box. If necessary, use the scroll bar at the right of the box to scroll through the list of impedances. The routine also computes the approximate bandwidth, the radiation efficiency, the front-to-back ratio, and the directivity of the antenna.

At this point you can plot the impedance locus versus frequency on a Smith chart plot or a VSWR/Return Loss plot, and can save the impedance data in a data file. Pattern plots can be made in the E- and H-planes of the patch, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button.

Validation

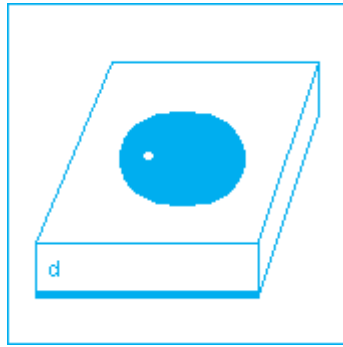
Consider a rectangular aperture coupled microstrip antenna with the following parameters:

Antenna substrate dielectric constant:	2.54
Antenna substrate thickness:	0.16 cm
Patch length:	4.0 cm
Patch width:	3.0 cm
Feed substrate dielectric constant:	2.54
Feed substrate thickness:	0.16 cm
Slot length:	1.12 cm
Slot width:	0.155 cm
Feed line width:	0.442 cm
Stub length:	2.0 cm

Calculated data using the model of [16] are compared with PCAAD at $f = 2.217$ GHz:

Quantity	Reference [16]	PCAAD 6.0
Input impedance	$65 -j 17 \Omega$	$64 -j 0.8 \Omega$
Gain (efficiency \times directivity)	6.2 dB	6.1 dB
Front-to-back ratio	23 dB	25 dB

F.6. Circular Probe-Fed Patch Analysis



This routine analyzes a circular probe-fed microstrip antenna using a cavity model similar to that discussed in reference [9]. The patch is treated as a lossy cavity to account for radiation, and length extensions are used to account for fringing fields at the patch edge. A parallel RLC equivalent circuit is then used to compute the input impedance versus frequency. The radiation patterns are found from the equivalent magnetic currents for the dominant TM_{11} mode. The directivity is calculated by integrating the

far-field patterns. This solution generally gives good results for microstrip antennas on thin substrates with low dielectric constants.

Enter the patch radius, the radial distance to the feed probe, the substrate thickness, the dielectric constant, and the dielectric loss tangent. The routine will then estimate the resonant frequency of the antenna, and suggest a frequency step size. These values are displayed, along with the default number of frequency points, in three boxes to the right of the **Compute** button. Click the **Compute** button to accept these values for the frequency sweep, or enter new values for the sweep center frequency, the frequency step size, or the number of frequency points. The routine will then compute the input impedance of the antenna over this frequency sweep, and display the results in the list box. If necessary, use the scroll bar at the right of the box to scroll through the list of impedances. The routine also computes the approximate bandwidth, the radiation efficiency, and the directivity of the antenna.

At this point you can plot the impedance locus versus frequency on a Smith chart plot or a VSWR/Return Loss plot, and can save the impedance data in a data file. Pattern plots can be made in the E- and H-planes of the patch, or E-theta / E-phi or Co-pol / X-pol patterns can be made at an arbitrary azimuth angle. Patterns can be plotted in polar, rectangular, or volumetric (3-D) form, and patterns can be saved as data files. Select the pattern type and parameters with the **Pattern Type Select** button.

Validation #1

Consider a circular probe-fed patch with a radius of 6.7 cm, on a substrate with a dielectric constant of 2.62 and a thickness of 0.16 cm, and a probe positioned 5.03 cm from the center of the patch. This example is given in [8] using a different cavity model, and compared with the following results from PCAAD:

Quantity	Reference [8]	PCAAD 6.0
Resonant frequency	793 MHz	796 MHz
Resonant resistance	180 Ω	219 Ω

Validation #2

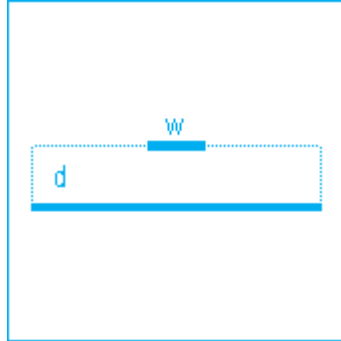
Consider a circular probe-fed patch with a radius of 2.78 cm on a substrate with a dielectric constant of 2.32 and a thickness of 0.16 cm, and a feed probe at the edge of the patch. Reference [9] gives the following data, compared with PCAAD:

Quantity	Reference [9]	PCAAD 6.0
Resonant frequency	2.00 GHz	1.996 GHz
Directivity	7.1 dB	7.1 dB
Bandwidth	1.1 %	1.3 %
E-plane 3 dB beamwidth	100°	103°
H-plane 3 dB beamwidth	80°	81°

G. The Transmission Lines and Waveguides Menu

This set of eight routines provide solutions for the analysis and design of several types of transmission lines and waveguides that are commonly used in microwave and antenna systems. Included are analysis and design solutions for microstrip line and stripline, and analysis solutions for covered microstrip line, coaxial line, rectangular waveguide, circular waveguide, and surface waves on a grounded dielectric substrate. Also included is a routine that lists data for standard rectangular waveguide.

G.1. Microstrip Line Analysis and Design



This routine is used to find the characteristic impedance of a microstrip transmission line, given the substrate parameters and line width, or to find the line width, given the substrate parameters and the characteristic impedance. Attenuation due to conductor and dielectric loss can also be calculated, if desired. These solutions employ closed-form quasi-static formulas that generally give good results for most practical design problems, as discussed in reference [10].

First choose either the **Compute Zo** option, or the **Compute width** option, by clicking the appropriate button at the left side of the window. This will change the input statements for the relevant data entry. When computing characteristic impedance, you will enter the dielectric constant, the substrate spacing, and the line width. Click the **Compute Zo** button to compute and print the characteristic impedance and the effective dielectric constant for the line. When calculating line width for microstrip design, you will enter the characteristic impedance, the dielectric constant, and the substrate thickness. Click the **Compute width** button to compute and print the required line width, and the effective dielectric constant for the line.

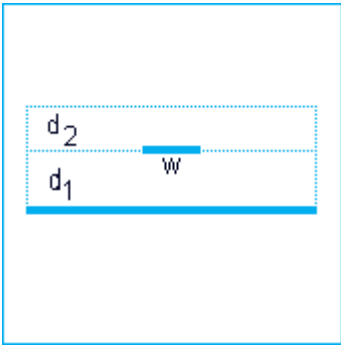
You may compute the attenuation for the line for either the line analysis or the line design case. Enter the frequency, the loss tangent of the dielectric filling material, and the conductivity of the microstrip conductors. The conductivity may be entered as a value in Siemens/meter, or a specific conductor material can be selected from the drop-down menu at the right of the conductivity box. Click the **Compute Attenuation** button, and the attenuation due to dielectric loss, conductor loss, and the total attenuation will be printed in dB/cm.

Validation

Consider the design of a $50\ \Omega$ microstrip line on a substrate with a dielectric constant of 2.08 and a thickness of 0.159 cm, at a frequency of 5 GHz. The conductors are copper and the dielectric loss tangent is 0.0004. This example corresponds to Example 6.2 in [10], and results from [10] are compared with PCAAD below:

Quantity	Reference [10]	PCAAD 6.0
Line width	0.508 cm	0.508 cm
Effective permittivity	1.80	1.806
Conductor attenuation	0.00629 dB/cm	0.0049 dB/cm
Dielectric attenuation	0.00208 dB/cm	0.0021 dB/cm

G.2. Covered Microstrip Line Analysis



This routine implements a full-wave moment method solution for the analysis of microstrip line with an optional cover layer. The effective dielectric constant, the characteristic impedance, and the attenuation constant are computed. This is a rigorous spectral domain solution using the exact Green's function for a two-layer dielectric medium, with the spectral perturbation technique [23] for calculating the attenuation constant.

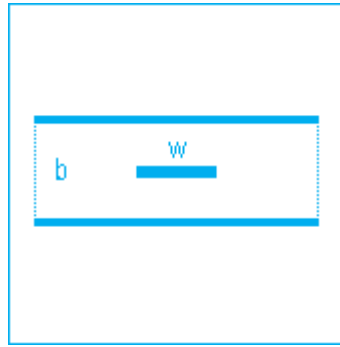
Begin by entering the bottom layer substrate parameters (thickness, dielectric constant, and loss tangent), then the cover layer parameters (thickness, dielectric constant, and loss tangent). Set the cover layer thickness to zero if no cover is present (in this case, the cover layer dielectric constant is not relevant, but must be set to a value greater than unity). Then enter the frequency, line width, and the conductivity of the line. The conductivity may be entered as a value in Siemens/meter, or a specific conductor material can be selected from the drop-down menu at the right of the conductivity box. Click the **Compute** button, and the effective dielectric constant, the characteristic impedance, and the total attenuation (in dB/cm) will be printed. The attenuation includes dielectric loss and loss due to finite conductivity of the strip; loss in the ground plane is not included.

Validation

Consider a microstrip line etched on a substrate with a dielectric constant of 2.2, a thickness of 0.16 cm, and a loss tangent of 0.01, with a cover layer having a dielectric constant of 2.2, a thickness of 0.16 cm, and a loss tangent of 0.01. The copper line is 0.4 cm wide. At 4 GHz, the following results are obtained and compared with PCAAMT, an independent full-wave model:

Quantity	PCAAMT	PCAAD 6.0
Effective permittivity	2.098	2.100
Characteristic impedance	53.2 Ω	54.8 Ω
Attenuation	0.053 dB/cm	0.054 dB/cm

G.3. Stripline Analysis and Design



This routine is used to find the characteristic impedance of a stripline transmission line, given the substrate parameters and line width, or to find the line width, given the substrate parameters and the characteristic impedance. Attenuation due to conductor and dielectric loss can also be calculated, if desired. These solutions employ closed-form quasi-static formulas that generally give good results for most practical design problems, as discussed in reference [10].

First choose either the **Compute Zo** option or the **Compute width** option, by clicking the appropriate radio button at the left side of the window. This will change the input statements for the relevant data entry. When computing characteristic impedance, you will enter the dielectric constant, the ground plane spacing, the line width, and the strip thickness. Click the **Compute Zo** button to compute and print the characteristic impedance and the cut-off frequency of the parallel-plate waveguide mode. When calculating line width for stripline design, you will enter the characteristic impedance, the dielectric constant, the ground plane spacing, and the strip thickness. Click the **Compute width** button to compute and print the required line width, and the cut-off frequency of the parallel-plate waveguide mode.

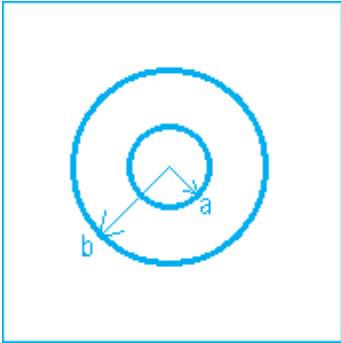
You may compute the attenuation for the line for either the line analysis or the line design case. Enter the frequency, the loss tangent of the dielectric filling material, and the conductivity of the stripline conductors. The conductivity may be entered as a value in Siemens/meter, or a specific conductor material can be selected from the drop-down menu at the right of the conductivity box. Click the **Compute Attenuation** button, and the attenuation due to dielectric loss, conductor loss, and the total attenuation will be printed in dB/cm.

Validation

Consider the design of a 50 Ω stripline at 10 GHz on a substrate with a dielectric constant of 2.2 and a ground plane spacing of 0.32 cm. The thickness of the strip is 0.001 cm, the conductors are copper, and the dielectric loss tangent is 0.001. This example corresponds to Example 3.5 in [10], and results from [10] are compared with PCAAD below:

Quantity	Reference [10]	PCAAD 6.0
Line width	0.266 cm	0.262 cm
Conductor attenuation	0.0106 dB/cm	0.0105 dB/cm
Dielectric attenuation	0.0135 dB/cm	0.0135 dB/cm

G.4. Coaxial Line Analysis



This routine computes the characteristic impedance and attenuation due to dielectric loss and conductor loss for a coaxial line. It also computes the cut-off frequency of the TE₁₁ waveguide mode of the coaxial line. The formulas used in this routine are standard results, as found in reference [10].

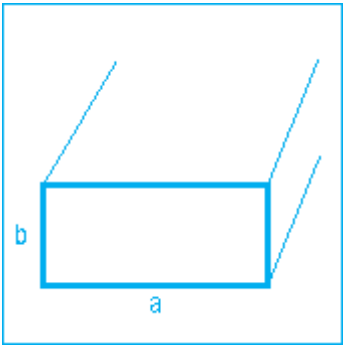
Begin by entering the inner conductor radius, the outer conductor radius, and the dielectric constant. Click the **Compute Zo** button, and the routine will compute and print the characteristic impedance of the coaxial line and the approximate cut-off frequency of the TE₁₁ waveguide mode. You can compute attenuation for the coaxial line by entering the frequency, the loss tangent of the dielectric filling material, and the conductivity of the coax conductors. The conductivity may be entered as a value in Siemens/meter, or a specific conductor material can be selected from the drop-down menu at the right of the conductivity box. Click the **Compute Attenuation** button, and the attenuation due to dielectric loss, conductor loss, and the total attenuation will be printed in dB/cm.

Validation

Consider a copper coaxial line with an inner conductor radius of 0.5 mm, an outer conductor radius of 1.5 mm, a dielectric constant of 2.5, and a loss tangent of 0.01, operating at 10 GHz. The formulas in [10] give the following results compared with PCAAD:

Quantity	Reference [10]	PCAAD 6.0
Characteristic impedance	41.7 Ω	41.7 Ω
TE ₁₁ mode cutoff frequency	30.2 GHz	30.2 GHz
Conductor attenuation	0.0115 dB/cm	0.012 dB/cm
Dielectric attenuation	0.145 dB/cm	0.144 dB/cm

G.5. Rectangular Waveguide Analysis



This routine computes the cut-off frequencies and propagation constants for the five lowest order modes of a rectangular waveguide, and the attenuation due to dielectric and conductor losses for the TE_{10} mode. Begin by entering the E-plane (narrow wall) and H-plane (broad wall) inside dimensions of the guide, the dielectric constant of the material filling the guide, and the operating frequency. Click the **Compute** button, and the routine will compute and print the cutoff frequencies of the (1,0), (2,0), (0,1), (1,1), and (0,2) modes; if the mode is propagating at the specified frequency, the propagation constant will also be printed, otherwise it is listed as cut-off. The formulas used in this routine are standard results, as found in reference [10].

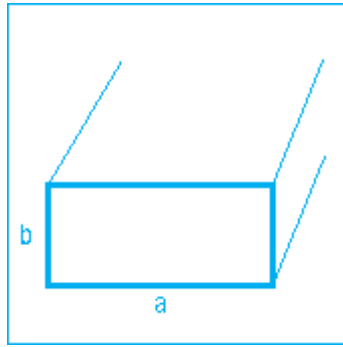
You can compute attenuation for the dominant TE_{10} mode, if it is propagating, by entering the loss tangent of the dielectric filling material and the conductivity of the waveguide walls. The conductivity may be entered as a value in Siemens/meter, or a specific conductor material can be selected from the drop-down menu at the right of the conductivity box. Click the **Compute Attenuation** button, and the attenuation due to dielectric loss, conductor loss, and the total attenuation will be printed in dB/cm.

Validation

Consider a copper K-band waveguide of dimensions $1.07\text{ cm} \times 0.43\text{ cm}$, operating at 15 GHz. The guide is filled with Teflon (dielectric constant of 2.08, loss tangent of 0.0004). This problem is treated in Example 3.1 of [10], and the results are compared with those from PCAAD below:

Quantity	Reference [10]	PCAAD 6.0
(1,0) mode cutoff frequency	9.72 GHz	9.720 GHz
(2,0) mode cutoff frequency	19.44 GHz	19.440 GHz
(0,1) mode cutoff frequency	24.19 GHz	24.188 GHz
(1,1) mode cutoff frequency	26.07 GHz	26.068 GHz
TE_{10} propagation constant	345.1 rad/m	345.08 rad/m
Conductor attenuation	0.00434 dB/cm	0.00433 dB/cm
Dielectric attenuation	0.0103 dB/cm	0.01034 dB/cm

G.6. Standard Rectangular Waveguide Data

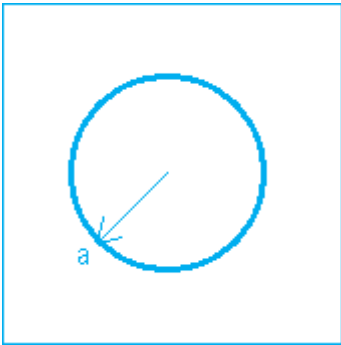


This routine lists data for standard rectangular waveguide, including the WR-number, the standard band letter designation, the recommended operating frequency range, the cut-off frequency for the TE_{10} mode, and the inner dimensions of the guide. The scroll bar at the right side of the list box can be used to scroll the entries up or down. The source data for this routine is stored in the ASCII file `RECWGDATA.DAT`, which you may edit to add or change the data displayed by PCAAD 6.0.

The data for each guide is entered on a separate line, with spaces or tabs as delimiters between the data elements.

The routine also allows you to send dimensions for a particular guide to the rectangular waveguide analysis routine (Section G.5), for convenient calculation of propagation constants, higher-order mode cutoff frequencies, or attenuation. Select a waveguide by clicking on the appropriate line in the list box (the line will be highlighted), then click the **Send to Rec. WG** button. The window for the **Standard Rectangular Waveguide Data** routine will close, and the **Rectangular Waveguide Analysis** window will open, with the dimensions for the selected guide automatically entered in the appropriate data boxes.

G.7. Circular Waveguide Analysis



This routine computes the cut-off frequencies and propagation constants for the five lowest order modes of a circular waveguide, and the attenuation due to dielectric and conductor losses for the dominant TE_{11} mode. Begin by entering the inside radius of the guide, the dielectric constant of the material filling the guide, and the operating frequency. Click the **Compute** button, and the routine will compute and print the cutoff frequencies of the TE_{11} , TM_{01} , TE_{21} , TE_{01} , and TM_{11} modes; if the mode is propagating at the specified frequency, the propagation constant will also be printed, otherwise it is listed as cut-off. The formulas used in this routine are standard results, as found in reference [10].

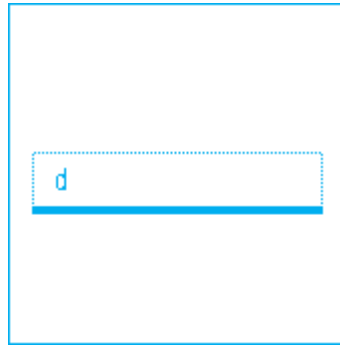
You can compute attenuation for the dominant TE_{11} mode, if it is propagating, by entering the loss tangent of the dielectric filling material and the conductivity of the waveguide walls. The conductivity may be entered as a value in Siemens/meter, or a specific conductor material can be selected from the drop-down menu at the right of the conductivity box. Click the **Compute Attenuation** button, and the attenuation due to dielectric loss, conductor loss, and the total attenuation will be printed in dB/cm.

Validation

Consider a circular waveguide with an inner radius of 0.5 cm, filled with Teflon (dielectric constant of 2.08, loss tangent of 0.0004). The waveguide is gold plated, and is operating at 14 GHz. This problem is presented as Example 3.2 in [10], with results compared to PCAAD below:

Quantity	Reference [10]	PCAAD 6.0
(1,1) mode cutoff frequency	12.19 GHz	12.190 GHz
(0,1) mode cutoff frequency	15.92 GHz	15.924 GHz
TE_{11} propagation constant	208.0 rad/m	207.984 rad/m
conductor attenuation	0.00583 dB/cm	0.0058 dB/cm
dielectric attenuation	0.0149 dB/cm	0.0149 dB/cm

G.8. Surface Wave Analysis



This routine computes TM and TE surface wave propagation constants for a grounded dielectric substrate. It first determines the number of propagating surface wave modes on the slab, then uses a Newton-Raphson iteration technique to find the propagation constants. It is based on standard results, as found in reference [10].

Enter the frequency, the substrate dielectric constant, and the substrate thickness. Click the **Compute** button to print out the normalized (to

k_0) propagation constant for each propagating surface wave mode. The routine also computes and prints an approximate value for the radiation efficiency of a printed antenna on this substrate. This efficiency is based on power lost to surface waves, and is meaningful because it has been shown that this type of radiation efficiency is fairly independent of the type or size of the actual radiating element, depending primarily on the substrate dielectric constant and thickness, as discussed in reference [17].

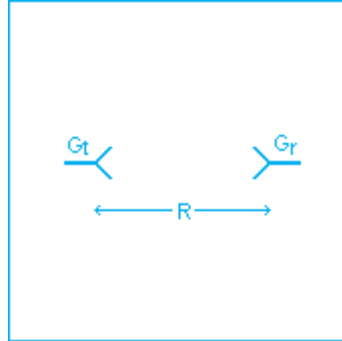
Validation

Consider the surface wave for a substrate with a dielectric constant of 2.55 and a thickness of 0.19 cm, operating at 30 GHz. This case occurs in [13], where the normalized propagation constant is given as $\beta/k_0 = 1.283$; PCAAD gives a value of 1.28249.

H. The Miscellaneous Menu

This set of six routines provide several solutions and data for a variety of topics related to antennas and applications. Included are routines for calculating communication link loss, the polarization mismatch between two antennas, the degradation in axial ratio caused by amplitude and phase errors, graphs for atmospheric attenuation and antenna temperature, and a calculator for useful microwave and antenna functions.

H.1. Communication Link Loss



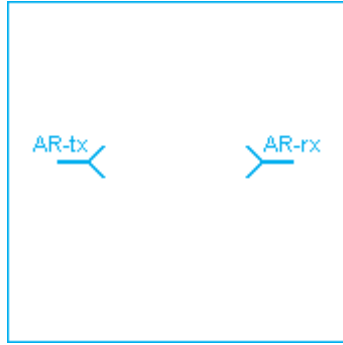
This routine computes the link loss for a radio communications link using the Friis formula [2], [3], [10].

Enter the gains of the transmit and receive antennas, the range between transmitter and receiver, the frequency, the polarization mismatch (enter 0 dB for no mismatch), and the atmospheric attenuation. The routine calculates the link loss assuming matched antennas.

Validation

Example 13.4 of [10] describes the link loss of a DBS satellite, with a transmit antenna gain of 34.0 dB, a receive antenna gain of 33.5 dB, a range of 39,000 km, and an operating frequency of 12.45 GHz. PCAAD gives a link loss of 138.7 dB, in agreement with the result of [10].

H.2. Polarization Mismatch Between Two Antennas



This routine calculates the maximum and minimum polarization mismatch between two arbitrarily polarized antennas using the formulation presented in [24].

Enter the axial ratio of each antenna, and specify the polarization sense (right hand or left hand). For an ideal linearly polarized antenna, enter a large value, such as 100 dB, for its axial ratio. The routine then computes the maximum and minimum losses due to polarization

mismatch. Note that these values, being defined as losses, appear as positive dB. The actual loss in practice will depend on the relative orientation of the polarization ellipses of the two antennas, but will always be between the minimum and maximum values given by this routine.

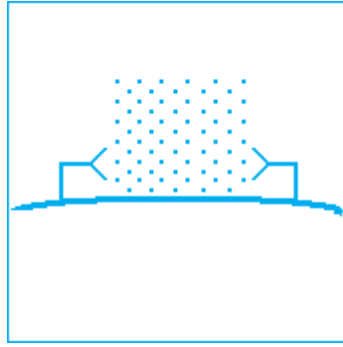
Validation #1

Consider the mismatch between an ideal circularly polarized antenna and an ideal linearly polarized antenna. By entering 0 dB for the axial ratio of the circularly polarized antenna, and 100 dB for the axial ratio of the linearly polarized antenna, PCAAD gives a minimum and maximum mismatch loss of 3.01 dB, as expected.

Validation #2

Consider a RHCP antenna with an axial ratio of 8 dB, and a RHCP antenna with an axial ratio of 4 dB. PCAAD gives the minimum and maximum mismatch losses as 0.15 dB and 1.85 dB. These values are in agreement with an example in [24].

H.3. Atmospheric and Rain Attenuation

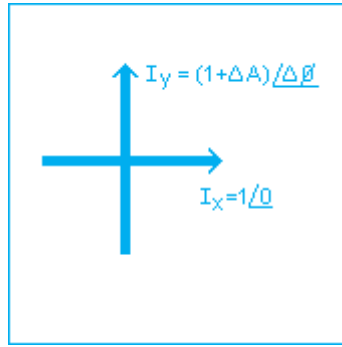


This routine presents a graph of atmospheric attenuation versus frequency, along with attenuation due to rain, as given in [8]. The atmospheric attenuation is at sea level, while the rain attenuation is given for three different rain rates.

Validation

At a frequency of 60 GHz, the attenuation rate of the atmosphere is 15 dB/km. At 40 GHz, the attenuation due to rain at a rate of 1 mm/hr is 0.33 dB/km; rain at the rate of 16 mm/hr increases to 4.9 dB/km.

H.4. Axial Ratio versus Amplitude and Phase Error



Many circularly polarized antennas are constructed using two orthogonal linearly polarized antennas fed with equal amplitude excitations that are 90 degrees out of phase. As presented in [25], this routine gives the resulting axial ratio due to errors in the actual amplitudes and phases.

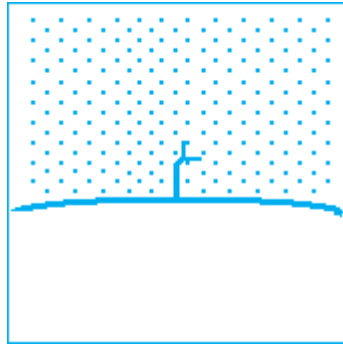
Enter the amplitude error (in dB), and the phase error (in degrees). The resulting axial ratio is calculated. Changing the sign of the

amplitude error, or the phase error, does not change the resulting axial ratio. A graph illustrating constant axial ratio contours versus amplitude and phase errors is also shown - this can be useful for estimating the amplitude and phase accuracies required for a given axial ratio.

Validation

For two orthogonal linearly polarized antennas having excitations with zero phase error and 3 dB amplitude error, PCAAD gives an axial ratio of 3 dB, in agreement with the graph, and with the results in [25]. For the case of zero amplitude error and a phase error of 30°, PCAAD gives an axial ratio of 4.8 dB, in agreement with the graph, and with the results in [25].

H.5. Antenna Noise Temperature



This routine presents a graph of the background noise temperature for an ideal (lossless) antenna, versus frequency and elevation angle (elevation angle is measured from the horizon, so $\theta = 90^\circ$ is overhead). The antenna is assumed to have a narrow pencil beam, with no sidelobes pointed toward the earth. Results are given for various elevation angles (measured from the horizon). The minimum and maximum noise temperatures are also shown. This data is

taken from [27].

Validation

At a frequency of 2 GHz, a narrow beam antenna pointed directly overhead will see an apparent noise temperature of about 9 K. An antenna with a more omnidirectional pattern will see a noise temperature as high as 100 K.

H.6. Microwave and Antenna Calculator



This routine provides a calculator function for three different types of conversions: conversion of dimensions (between meters, centimeters, millimeters, inches, and mils), conversion of return loss and VSWR (between return loss, reflection coefficient magnitude, VSWR, and mismatch loss), and conversion of dB and ratios (between ratios in dB, nepers, power ratios, and voltage ratios). Each of these functions operate in the same way. Simply enter the known value in the

appropriate text box, press **Enter**, and the converted values will appear in the remaining boxes. Note that all dimensions must be greater than zero; return loss, reflection coefficient magnitude, mismatch loss, voltage ratio, and power ratio must be non-negative; and VSWR must be unity or larger.

Validation

Consider an antenna having an input VSWR of 2.0. Entering this value in the VSWR box of the calculator routine and pressing **Enter** shows that the input reflection coefficient magnitude is 0.3333, the input return loss is 9.54 dB, and the mismatch loss is 0.512 dB.

V. References

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